Appendix E – Model Documentation

Introduction

Washington State Department of Ecology developed a dynamic one-dimensional QUAL2Kw (Version 6.0) model of the Pilchuck River to simulate biological productivity and diel pH swings. Ecology developed and calibrated the model using data collected in the summer of 2012. Details of the data collection, study area, and project goals and objectives are available in the QAPPs (Swanson, et al, 2012; Mathieu, 2014; Mathieu, 2016) and the main body of this report.

This appendix documents the development, calibration, and model quality analysis of the 2012 Pilchuck River QUAL2KW model.

QUAL2Kw Modeling Framework

The QUAL2Kw 6.0 modeling framework (Pelletier and Chapra, 2008) was used to develop the loading capacity for nutrients and to make predictions about water quality under various scenarios. The QUAL2Kw model framework and complete documentation are available at http://www.ecy.wa.gov/programs/eap/models html.

The QUAL2Kw 6.0 modeling framework has the following characteristics:

- One dimensional. The channel is well-mixed vertically and laterally. Also includes up to two optional transient storage zones connected to each main channel reach (surface and hyporheic transient storage zones).
- Non-steady, non-uniform flow using kinematic wave flow routing. Continuous simulation with time-varying boundary conditions for periods of up to one year.
- Dynamic heat budget. The heat budget and temperature are simulated as a function of meteorology on a continuously varying or repeating diel time scale.
- Dynamic water-quality kinetics. All water quality state variables are simulated on a continuously varying or repeating diel time scale for biogeochemical processes.
- Heat and mass inputs. Point and non-point loads and abstractions are simulated.
- Phytoplankton and bottom algae in the water column, as well as sediment diagenesis, and heterotrophic metabolism in the hyporheic zone are simulated.

- Variable stoichiometry. Luxury uptake of nutrients by the bottom algae (periphyton) is simulated with variable stoichiometry of N and P.

The previous versions of Ecology's QUAL2Kw modeling framework assume flows are constant, and other boundary conditions are represented by a repeating diel pattern. Ecology recently updated QUAL2Kw to include use of the kinematic wave (KW) method of flow routing (Chapra, 1997) for simulation of continuously changing channel velocity and depth in response to changing flows. In addition, the updated QUAL2Kw framework allows input of continuous changes in other boundary conditions (e.g., tributary loading and meteorology). Incorporation of KW transport and continuous boundary forcing now allows QUAL2Kw to be used to simulate continuous changes in water quality for up to a year.

The updated QUAL2Kw framework was selected because the dominant primary producers in the Pilchuck River are bottom algae and it was considered necessary to simulate continuous changes in nutrients, biomass, and pH over an entire growing season, including representation of diel variations. QUAL2Kw (with KW transport) is capable of dynamic simulation of river pH and includes kinetics that are representative of bottom algae as the dominant primary producers.

Within QUAL2Kw, hydrodynamics for each reach are simulated based on channel characteristics, user supplied flow parameters, and the one-dimensional KW method. The KW equation is used to drive advective transport through free-flowing segments and to calculate flows, volumes, depths, and velocities resulting from variable upstream inflow.

Ecology also used depth (from the 2014 float surveys), width (digitized from aerial photography), and velocity (2016 dye study) to develop the channel geometry for the QUAL2Kw model. Ecology used depth and width data from a range of flow conditions to generate power curves for the QUAL2Kw channel geometry.

Ecology used two additional tools to develop the shade inputs for the QUAL2Kw model: Ttools, and the Shade model.

- The Oregon Department of Environmental Quality (ODEQ) and Ecology's TTools extension for ArcGIS (Ecology, 2015) was used to sample and process GIS data for input to the QUAL2Kw model.
    - Ecology has recently updated TTools with more modern python code and some additional improved features. This new version was used for the White River.
- Ecology's Shade.xlsm model (version 40b04a06; Pelletier, 2015)) was used to estimate effective shade along the mainstem of the Pilchuck River.
    - Effective shade was calculated at 50-meter intervals along the streams and then averaged within each model segment for input to the QUAL2Kw model.
    - The Shade model was adapted from a program also originally developed by the ODEQ as part of the HeatSource model. The Shade model uses (1) mathematical simulations to quantify potential daily solar load and generate percent effective

shade values, and (2) an effective shade algorithm, modified from Boyd (1996) using the methods of Chen et al. (1998a and 1998b).

  - Ecology recently updated the Shade model to simulate shade over a 365 day period (previously only 1 day simulation).

Ecology also used a tool called the River Metabolism Analyzer (RMA) (Pelletier, 2013) to estimate reaeration, primary productivity, ecosystem respiration, and sediment oxygen demand.

Modeling assumptions for this study

General

- The channel is generally well mixed vertically and laterally and can be represented in a one-dimensional model.
- Photosynthesis and respiration from attached benthic algae, or periphyton, are primarily responsible for diel swings in pH in the Pilchuck River.
- During periods when the river is not light limited (midday, sunny weather, low flow), periphyton is primarily limited by a single limiting nutrient at any given time, either phosphorus or nitrogen, depending on whichever nutrient is currently in the shortest supply relative to the cellular needs of the periphyton.
- Periphyton growth rates, in relation to nutrients, are controlled by intracellular concentrations, not external concentrations in the water column; and internal concentrations can differ from external because periphyton are capable of variable stoichiometry, or storing nutrients in excess of needs during periods of increased supply.
- Hyporheic flow occurs in all the model reaches, with increased hyporheic flow in the middle section of the river.
- Changes in periphyton and hyporheic biofilm productivity will be accurately represented by the model under conditions which are different than the calibrated model conditions (e.g. at lower flows or reduced nutrient loading).

Inputs

- Gaining groundwater reaches could be inferred from the results of flow balances, piezometer temperatures/water levels, and observations/measurements of seeps.
- Water quality samples collected from gaining piezometers and seeps are representative of water quality in groundwater discharging to the river.
- Continuous time series of nutrient concentrations for boundary conditions and sources, developed through interpolation between data points or regression with another time series record, are reasonably representative of nutrient loading during periods with no observed data.

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Model Setup

QUAL2Kw general settings

Ecology set-up the QUAL2Kw model as a continuous model simulating hydraulics, water quality, and periphyton growth for the period of 6/7/2012 to 10/9/12 (124 days) (Table E-1).

Table E-1. QUAL2Kw setup options for the 2012 Pilchuck River Model.

System ID:		
Month	6	
Day	7	
Year	2012	
Local standard time zone relative to UTC	-8	hours
Daylight savings time	No	
Simulation and output options:		
Calculation step	1.40625	minutes
Number of days for the simulation period	124	days
Simulation mode	Continuous	
Solution method (integration)	Euler	
Solution method (pH)	Newton-Raphson	
Simulate hyporheic transient storage zone (HTS)	Level 2	
Simulate surface transient storage zone (STS)	No	
Option for conduction to deep sediments in heat budget	Segmented	
State variables for simulation	All	
Simulate sediment diagenesis	No	
Simulate alkalinity change due to nutrient change	Yes	

QUAL2Kw Model Segmentation

The model divides the Pilchuck River into 40 segments of uniform length over the course of 25 river miles (~42 km) (Table E-2). The model is segmented into 1 kilometer reaches.

Ecology developed power rating curves to define the geometry in the QUAL2Kw model (Table E-2). Three data sources were used to develop these rating curves:

1. Segment-averaged depth values collected during the 2014 longitudinal depth surveys. Given that depths were collected in the thalweg of the stream (deeper than average depth) a factor of 0.9 (based on flow measurement transects) was applied to the thalweg depth values to estimate the average cross section depth.
2. Digitized wetted widths using National Agriculture Imagery Program (NAIP) aerial photography from the years 2009, 2011, 2013, and 2015. The aerial image dates were

used to relate the widths to river flows, the images were collected at range of flows from ~40 to 100 cfs.

3. Velocity curves were first estimated using the depth and width values, then adjusted based on the results of the time of travel study conducted in August 2016.

Table E-2. Model segment lengths, elevations, and rating curves for the QUAL2Kw model.

Reach		Reach length (km)	Channel Slope	D/S location (km)	Elevation		Velocity rating curve		Width rating curve	
Label	Number				U/S (m)	D/S (m)	a	b	a	b
Headwater	0			42.2		133.5	0.19	0.68	16.1	0.27
PIL25.5 - Menzel Lake Rd	1	1.20	0.0040	41	133.4	128.7	0.19	0.68	16.1	0.27
	2	1.00	0.0047	40	128.7	124.0	0.23	0.63	15.7	0.29
	3	1.00	0.0035	39	124.0	120.5	0.20	0.32	14.3	0.40
	4	1.00	0.0037	38	120.5	116.8	0.26	0.38	15.3	0.16
	5	1.00	0.0040	37	116.8	112.8	0.24	0.37	14.4	0.27
	6	1.00	0.0031	36	112.8	109.7	0.25	0.26	15.2	0.27
PIL21.5 - Robe Menzel Rd	7	1.00	0.0062	35	109.7	103.5	0.32	0.17	16.2	0.36
	8	1.00	0.0044	34	103.5	99.1	0.19	0.74	14.2	0.21
	9	1.00	0.0039	33	99.1	95.2	0.24	0.16	15.0	0.46
	10	1.00	0.0036	32	95.2	91.6	0.28	0.64	12.6	0.31
	11	1.00	0.0046	31	91.6	87.0	0.19	0.67	12.6	0.28
PIL18.7 - Ray Gray Rd	12	1.00	0.0036	30	87.0	83.4	0.17	0.60	12.3	0.35
	13	1.00	0.0020	29	83.4	81.4	0.27	0.28	17.0	0.23
	14	1.00	0.0006	28	81.4	80.8	0.15	0.39	14.2	0.45
	15	1.00	0.0056	27	80.8	75.2	0.39	0.34	11.3	0.44
	16	1.00	0.0025	26	75.2	72.7	0.31	0.24	13.9	0.40
	17	1.00	0.0032	25	72.7	69.5	0.25	0.53	14.7	0.28
PIL15.1 - 64th	18	1.00	0.0027	24	69.5	66.8	0.28	0.17	11.6	0.53
	19	1.00	0.0011	23	66.8	65.7	0.25	0.56	12.9	0.23
	20	1.00	0.0020	22	65.7	63.7	0.21	0.57	13.7	0.35
	21	1.00	0.0054	21	63.7	58.3	0.22	0.79	15.0	0.16
	22	1.00	0.0028	20	58.3	55.5	0.29	0.33	14.8	0.33
PIL 11.6 - 28th Pl NE	23	1.00	0.0026	19	55.5	52.9	0.19	0.83	15.7	0.12
	24	1.00	0.0028	18	52.9	50.1	0.24	0.58	15.2	0.35
	25	1.00	0.0032	17	50.1	46.9	0.32	0.26	14.3	0.30
PIL 10.4 - Russell Rd	26	1.00	0.0031	16	46.9	43.8	0.21	0.58	16.6	0.14
	27	1.00	0.0031	15	43.8	40.7	0.26	0.62	14.4	0.33
	28	1.00	0.0033	14	40.7	37.4	0.26	0.35	12.6	0.40
PIL 8.5 - OK Mill Rd	29	1.00	0.0029	13	37.4	34.5	0.15	0.76	16.6	0.19
	30	1.00	0.0018	12	34.5	32.7	0.20	0.78	16.5	0.19
	31	1.00	0.0050	11	32.7	27.7	0.31	0.31	14.0	0.45
	32	1.00	0.0020	10	27.7	25.7	0.25	0.50	17.0	0.31
PIL 5.7 - Dubuque Rd	33	1.00	0.0043	9	25.7	21.4	0.28	0.41	13.5	0.34
	34	1.00	0.0024	8	21.4	19.0	0.27	0.48	15.7	0.14
	35	1.00	0.0026	7	19.0	16.4	0.18	0.57	14.3	0.26
	36	1.00	0.0024	6	16.4	14.0	0.21	0.75	17.1	0.19
PIL 3.6 - Three Lakes Rd	37	1.00	0.0023	5	14.0	11.7	0.25	0.56	12.6	0.21
	38	1.00	0.0020	4	11.7	9.7	0.23	0.65	13.1	0.10

Commented [NE(4]: In the main report you typically use river miles It can be confusing switching back and forth I see that you have river miles listed under reach labels, but would it be worth adding a column for river miles to this table?

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PIL 2.0 - 6th St	39	1.00	0.0020	3	9.7	7.7	0.17	0.80	16.0	0.15
2nd St (Downstream Boundary)	40	1.00	0.0021	2	7.7	5.6	0.22	0.64	11.5	0.27

The headwater boundary condition was derived from time series and discrete data collected by Ecology at RM 25.5, at Menzel Lake Rd.

Significant inputs (Table E-33) within the model were represented in the continuous sources worksheet and included:

- Gaining groundwater input in 36 model segments (Reach 1-26, 28-33, 35, 37-40).
- Tributary (surface water) inputs in 17 segments (Reach 1, 8, 9, 12, 14, 17, 18, 23, 25, 29, 30, 31, 33, 35, 38, 39, and 40).
- Municipal wastewater treatment facility for the city of Granite Falls (Reach 11).

Ecology developed continuous flow inputs using the continuous USGS gage, results of the seepage surveys, and USGS StreamStats (Figure E-1). StreamStats was used to obtain estimates of peak 2 year storm flows for each tributary basin. A rating curve was the developed between the USGS gage on the Pilchuck River and each tributary using observed values and the StreamStats estimates.

Continuous dissolved oxygen inputs (Figure E-2) were constructed by 1) calculating the potential DO at saturation using temperature, specific conductance, and barometric pressure; and 2) using the observed daily variation in saturation from the synoptic surveys to estimate DO concentrations.

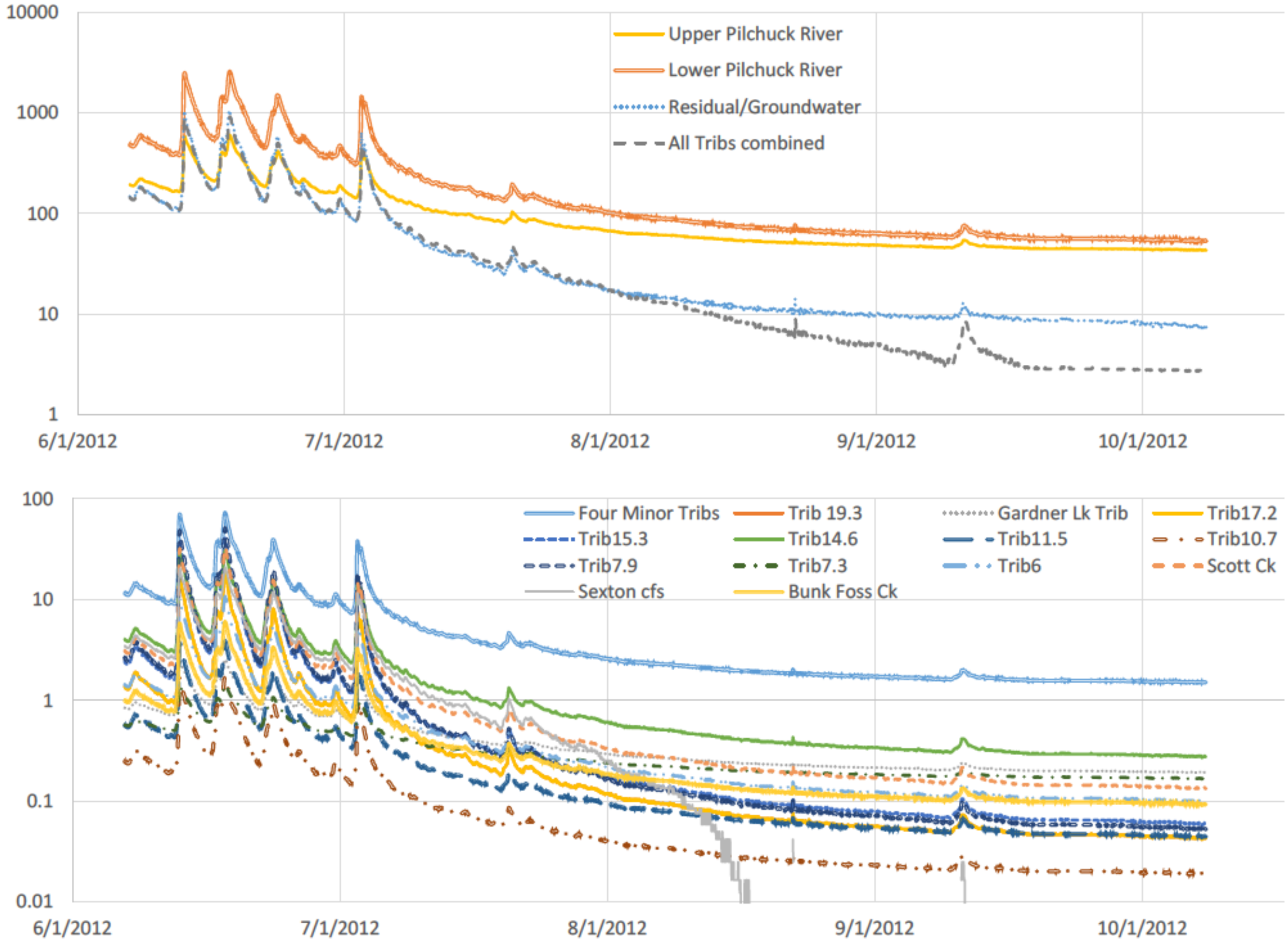

Figure E-1. Flow residuals and inputs for the 2012 model.

Figure E-2. Dissolved oxygen inputs/ boundary conditions for the 2012 model.

Table E-3. Inflows in the 2012 Pilchuck River QUAL2Kw model.

Reach Number	Inflow Source#1	Inflow Source#2	Inflow Source#3	Inflow Source#4
1	Groundwater	Purdy Creek		
2	Groundwater			
3	Groundwater			
4	Groundwater			
5	Groundwater			
6	Groundwater			
7	Groundwater			
8	Groundwater	Four Minor Tribs		
9	Groundwater	Trib 19.3		
10	Groundwater			
11	Groundwater		Granite Falls WWTP	
12	Groundwater	Garner Lk Trib		
13	Groundwater			
14	Groundwater	Trib 17.2		
15	Groundwater			
16	Groundwater			
17	Groundwater	Trib 15.3		
18	Groundwater	Trib 14.6		
19	Groundwater			
20	Groundwater			
21	Groundwater			
22	Groundwater			
23	Groundwater	Trib 11.5		
24	Groundwater			
25	Groundwater	Trib 10.7		
26	Groundwater			
27				
28	Groundwater			
29	Groundwater	Dubuque Creek		Little Pilchuck Creek
30	Groundwater	Trib 7.9		
31	Groundwater	Trib 7.3		
32	Groundwater			
33	Groundwater	Trib 6		
34				
35	Groundwater	Scott Creek		
36				
37	Groundwater			
38	Groundwater	Sexton Creek		
39	Groundwater	Bunk Foss Creek		
40	Groundwater			

QUAL2Kw Meteorology Inputs

Ecology used meteorology time series data from various external sources, as described in the main report. Shade input data was derived using the ArcGIS extension "Ttools" and Ecology's Shade xlsm model.

Shade model inputs

Near-stream vegetation cover, along with stream depth, air temperature and groundwater, represent the most important factors that influences stream temperature (Adams and Sullivan, 1989). To obtain a detailed description of existing riparian conditions in the Pilchuck River basin, a combination of GIS analysis, interpretation of aerial photography, and hemispherical photography was used.

A GIS coverage of riparian vegetation in the study area (Figure E-23) was created from:

1. Field notes and measured tree heights collected during riparian surveys Ecology conducted as part of the 2012 study.
2. Analysis of the color digital Snohomish County orthophotos from 2012.
3. Analysis of LIDAR (first return minus bare earth) data collected by Pierce County.

Polygons representing different vegetation types were mapped within a 300-foot buffer on either side of the river at a 1:2000 scale using GIS. Riparian vegetation was classified into vegetation categories (Table E-3). Each vegetation category was assigned three characteristic attributes: maximum height, average canopy density, and streambank overhang.

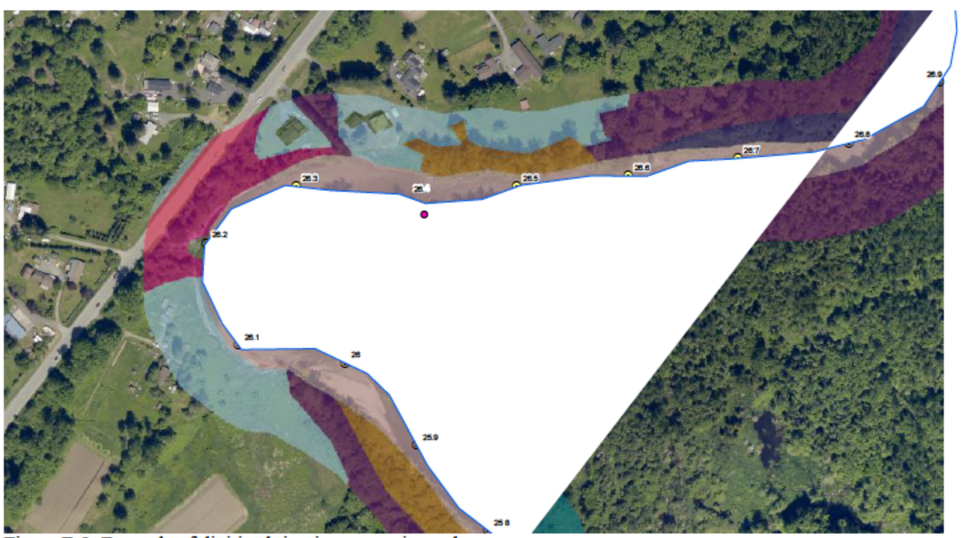

Figure E-3. Example of digitized riparian vegetation polygons.

After the vegetation polygons were delineated, a longitudinal profile of vegetation information along the Pilchuck River was created by sampling these polygons along the right and left banks of the stream at 50-meter intervals using GIS, using the TTools extension for ArcView. Stream aspect, elevation, and topographic shade angles to the west, south, and east were also calculated by TTools at each 50-meter interval using a digital elevation model (DEM).

The following settings were used when running TTools:

- Sampling was conducted at 50-m intervals along the mainstem of the Pilchuck River.
- LiDAR was used to determine the stream gradient using a 25-cell sample size, which is the maximum accuracy provided by TTools (cell sample size dictated by the input raster, therefore 6ft-by-6ft cells).
- 10-m DEM (Digital Elevation Model) was used for topographic shade angles because it was available for an extent beyond the immediate channel region, sampled to 10km away in 7 directions as the maximum accuracy provided by TTools.
- Vegetation sampling occurred at 6-m intervals into the riparian buffer (nine samples total within the 180-foot buffer width) perpendicular to the stream aspect. Sampling occurred for both left and right banks.

In addition to vegetation information, TTools was also used to sample each 50-m interval for channel wetted width, NSDZ width, stream aspect, stream elevation, and topographic shade angles in all directions. Using all of this relevant information, modeled effective shade was calculated based on channel geometry, vegetation, and solar position.

These settings were specified within the Shade model:

- Channel incision depth was estimated as the average incision measured from field sites.
- The Bras Method for the Solar Radiation model.
- The Chen Method of shade calculation: recommended for QUAL2Kw models.

The output from TTools was then used as an input into Ecology's Shade model (Ecology, 2008) to estimate effective shade along the Pilchuck River. Effective shade is defined as the fraction of incoming solar shortwave radiation above the vegetation and topography that is blocked from reaching the surface of the stream. Effective shade from 50m intervals was then averaged within each model reach for input into the QUAL2Kw model.

The initial riparian vegetation coding, Ttools analysis, and shade modeling was conducted by Tetra Tech (Kennedy and Nicholas, 2013). Ecology reviewed the analysis, made some minor modifications, re-ran TTools, and re-ran the shade model.

Most notably, Ecology adjusted the 'tall' riparian height classifications from 144 feet (44 m) to 100 feet (30.5 m) and then recalculated effective shade. Initially, Tetra Tech assigned the 'tall' riparian vegetation categories a height classification of 144 feet (44 m). Ecology compared this to 36 field measurements of this height class and found a significant bias. The field measured values ranged from 40 to 140 feet with a median of 100 feet (Figure E-14).

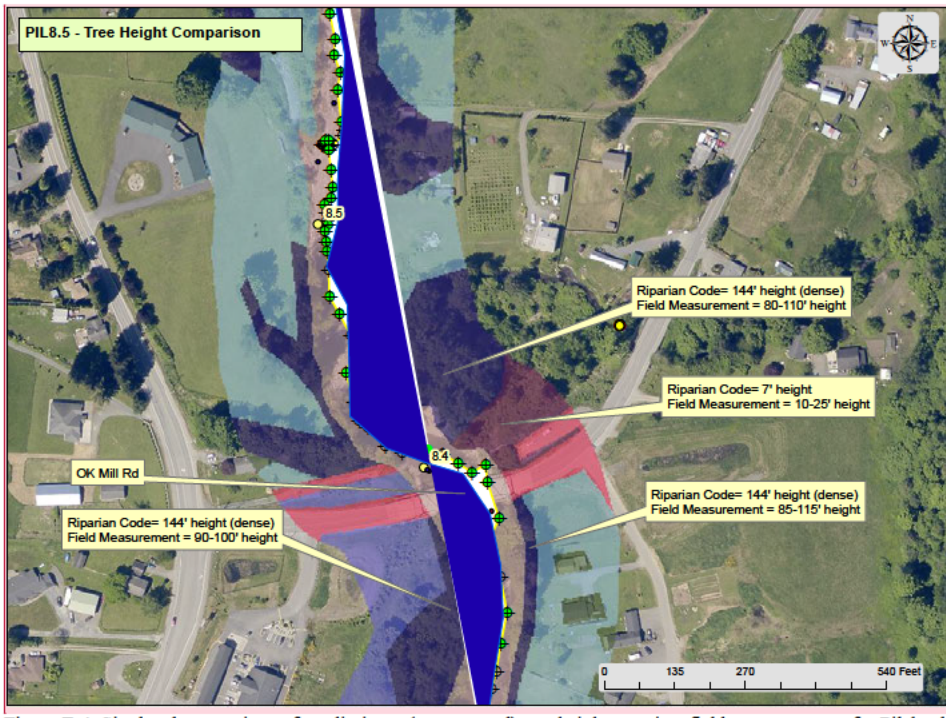

Figure E-4. Site level comparison of preliminary (uncorrected) tree heights against field measurements for Pilchuck River at OK Mill Rd.

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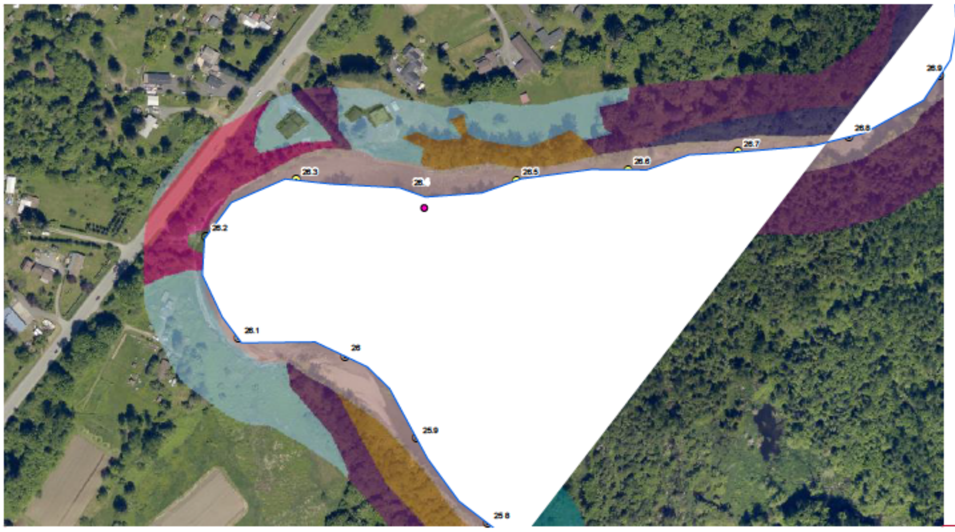
What are the "A" symbols for? Consider removing if not needed, or explain

Table E-3. Vegetation codes, heights, densities, and overhang values.

Description	Height (m)	Density (%)	OH (m)
Conifer-Small-Dense	4.2	75%	0.4
Conifer-Small-Sparse	4.2	25%	0.4
Conifer-Medium-Dense	21.3	75%	2.1
Conifer-Medium-Sparse	21.3	25%	2.1
Conifer-Tall-Dense	30.5	75%	3.1
Conifer-Tall-Sparse	30.5	25%	3.1
Deciduous-Small-Dense	4.2	75%	0.4
Deciduous-Small-Sparse	4.2	25%	0.4
Deciduous-Medium-Dense	21.3	75%	2.1
Deciduous-Medium-Sparse	21.3	25%	2.1
Deciduous-Tall-Dense	30.5	75%	3.1
Deciduous-Tall-Sparse	30.5	25%	3.1
MixeE-Small-Dense	4.2	75%	0.4
MixeE-Small-Sparse	4.2	25%	0.4
MixeE-Medium-Dense	21.3	75%	2.1
MixeE-Medium-Sparse	21.3	25%	2.1
MixeE-Tall-Dense	30.5	75%	3.1
MixeE-Tall-Sparse	30.5	25%	3.1
Shrub-Dense	2.0	75%	0.2
Shrub-Sparse	2.0	25%	0.2
Grass (non-residential)	0.5	100%	0.1
Grass (residential lawn)	0.5	100%	0.1
Water	0.0	100%	0.0
Pasture-Agriculture	0.0	100%	0.0
Road	0.0	100%	0.0
House	6.1	100%	0.0
Sand/Barren	0.0	100%	0.0
Clear-Cut Forest	0.0	100%	0.0
Gravel-pit/Industrial	0.0	100%	0.0
Powerline	0.0	100%	0.0
Open-Recreational	0.0	100%	0.0
Parking Lot	0.0	100%	0.0



Commented [NE(7]: Needs to show codes for vegetation polygons

There are numbers along the mainstem which are illegible

Needs scale and north arrow

QUAL2Kw hyporheic and light extinction settings

In general, Ecology used default rates, constants, kinetics and options for the initial model setup and systematically adjusted these variables during model calibration. In a few cases, Ecology made alterations prior to calibration including:

- The hyporheic transient storage zone was turned on to simulate potential effects of the hyporheic zone. The quality of the alluvial substrates and numerous field observations suggested that hyporheic flow was likely present throughout the study reach. Table E-4 contains parameters used for the hyporheic zone.
- The background and ISS light extinction rates were altered based on light extinction surveys from other Ecology studies (Table E-5).

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Table E-4. Thermal and hyporheic properties for the hyporheic transient storage zone for the QUAL2Kw model.

Reach Number	Sediment and hyporheic transient storage (HTS) zones					
	Sediment thermal conductivity (W/m/ degC)	Sediment thermal diffusivity (cm^2 /sec)	Sediment/ hyporheic zone thickness (cm)	Hyporheic Flow fraction (unitless)*	Hyporheic sediment porosity (fraction of volume)	Deep sediment temperature below sediment/HTS (deg C)
1 – 6	1.57	0.0064	20	0.1	0.4	13.5
6 – 33	1.57	0.0064	60	0.15	0.4	13.5
34 - 40	1.57	0.0064	20	0.1	0.4	13.5

* Parameter for diffusive exchange

Table E-5. Non-default light extinction rates for the QUAL2Kw model.

Parameter	Value	Unit
Background light extinction	1	*/m*
ISS light extinction	0.065	*1/m-(mgD/L)*

Model calibration

Hydraulics Calibration

To calibrate the velocity rating coefficients in the QUAL2Kw model, Ecology compared predicted time of travel data in QUAL2Kw with observed time of travel data from the 2016 dye study. The average absolute difference of predicted vs observed time of travel in the model was 2.5 hours (6% of total time of travel), with a range of 45 minutes to 4 hours (Figure E-5). Within the model, the August 2016 dye release (70-74 cfs) was simulated on 8/18/12 (73 cfs flow range). The velocity coefficients of the channel geometry were scaled in order to match the observed travel time.

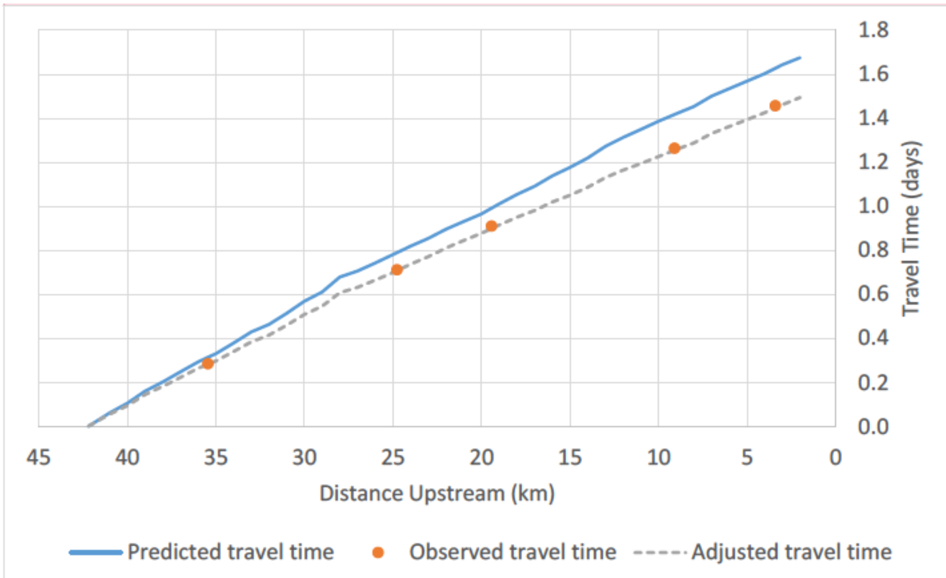

Figure E-5. Predicted and observed time of travel results, including model adjustment.

Flow Calibration

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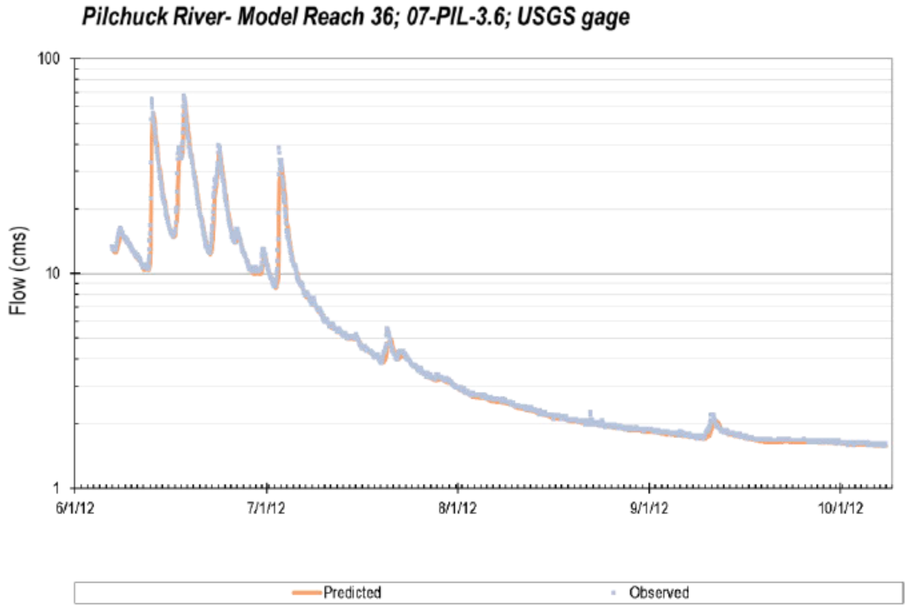
Suggest replacing the word "predicted" with "un-calibrated" and replacing "adjusted" with "calibrated"



Temperature Calibration

After Ecology completed calibration of the hydraulics and channel geometry, the initial goodness of fit for temperature was calculated using the root mean squared error (RMSE), as a measure of unbiased overall error, and the average difference between predicted and observed values, as a measure of the bias (hereafter referred to as just bias) (Table E-10). Error statistics were calculated on an hourly basis throughout the 124 day modeling period and represent a comprehensive goodness of fit for the entire diel cycle and multiple temperature regimes within the model period, rather than an evaluation of daily max/min/mean during critical conditions. In some reaches this represented the entire modeling window, while others had some data gaps.

Some parameters were adjusted and evaluations made to improve the temperature fitness. These measures included:

- Adjusting groundwater temperatures:
  - Ecology used a groundwater temperature of 13.5 °C based on the stable lowest thermistor temperature in the piezometer at Dubuque Rd. This also agreed with temperature measurements from seeps, which had a median temperature of 13.8 °C.
- Switching to Satterlund longwave radiation:
  - Switched from Brunt (default) to Satterlund model for longwave emissivity.

Commented [NE(12]: You could refer reader to shade calibration here (I forget where you show it), since that is relevant

Commented [NE(13]: Not defined yet Suggest defining these terms prior to this section

Commented [NE(14]: Incorrect table reference (this table is historic tree frequency) I don't know what table you mean, and I can't find a table showing your temperature error statistics right now Was it in the main report?

Commented [NE(15]: (new paragraph)

Commented [NE(16]: Maybe also state the values you used in Q2K for this model (is it Kcl1 and Kcl2 or something like that?)

- Adjusting hyporheic flow parameters:
  - Increased hyporheic zone thickness from 10 to 20-60 cm and flow fraction from 0.05 to 0.1 - 0.15 based on observed hyporheic flow throughout study area.

Commented [NE(17]: I worry about implying that you observed the zone thickness and flow fraction Maybe restate?

Table E-6. Selected (non-default) terms in 'Light and Heat'

Commented [NE(18]: Not referenced in text, may not merit a separate table if you write it into the text, but it's your call

Solar shortwave radiation		
Atmospheric attenuation model for solar	Observed	
Downwelling atmospheric longwave IR radiation		
atmospheric longwave emissivity model	Satterlund	

Ecology also evaluated fitness visually to assess calibration using longitudinal, diel, and dynamic temperature plots (Figures E-6 through E-8).

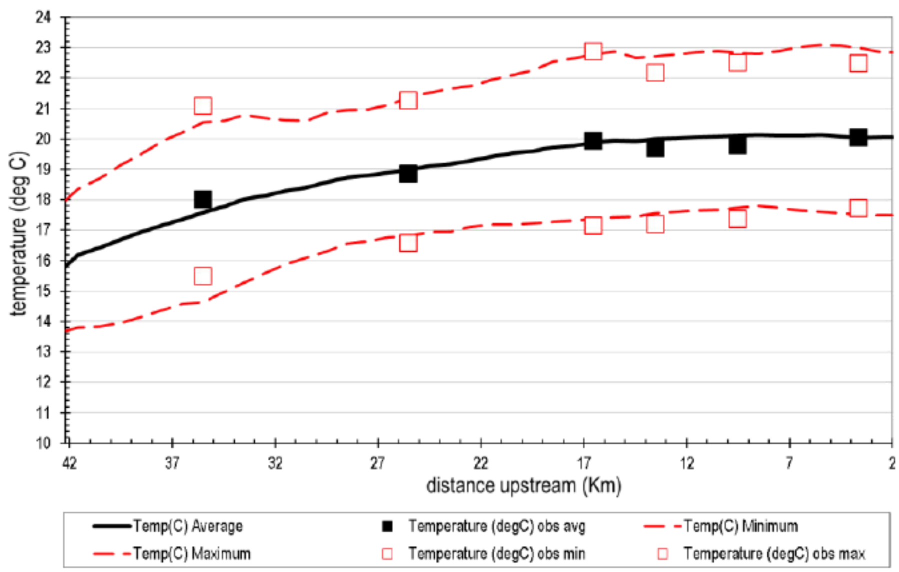


Figure E-6. Longitudinal temperature profile for 8/17/12 in the calibrated 2012 QUAL2Kw model.

Commented [NE(19]: Not referenced in text

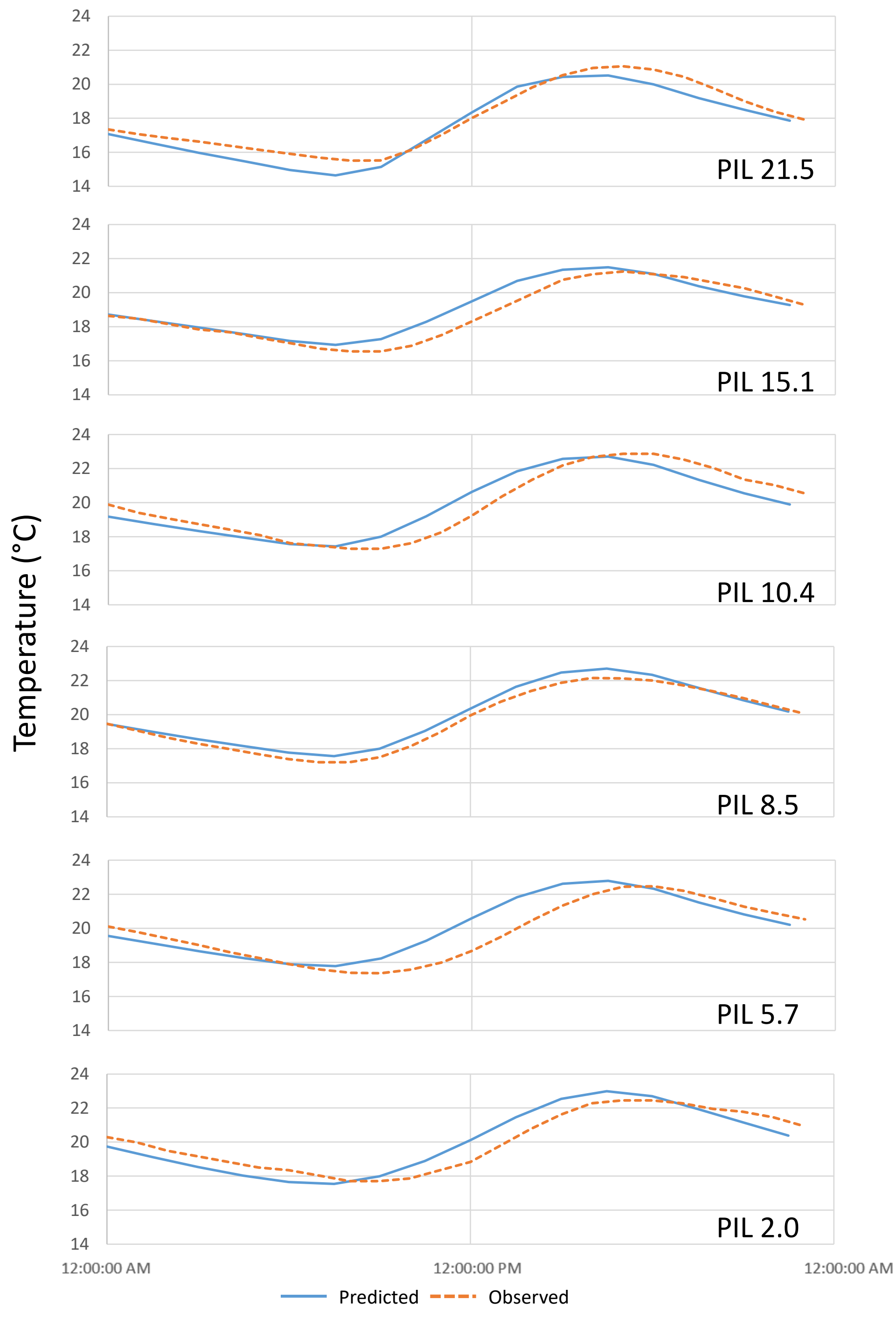

Temperature (°C)
24
22
20
18
16
14
PIL 21.5
PIL 15.1
PIL 10.4
PIL 8.5
PIL 5.7
PIL 2.0
12:00:00 AM
12:00:00 PM
12:00:00 AM
Predicted
Observed

Figure E-7. Predicted vs Observed Diel temperature for 8/17/12.

Commented [NE(20]: Not referenced in text

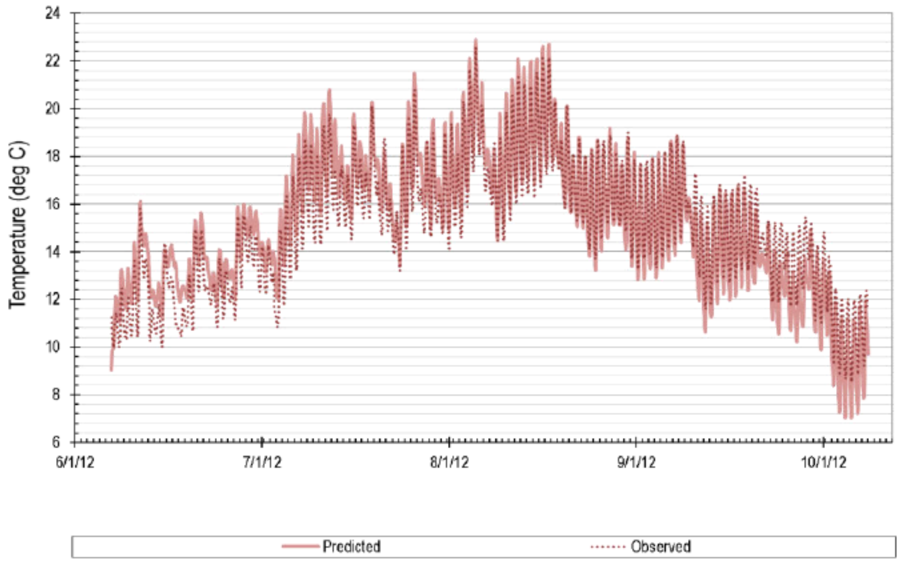


Figure E-8. Dynamic temperature goodness of fit for the calibrated model at Reach 29 (observed data from RM 8.5).

Commented [NE(21]: Not referenced in text

Overall the model describes the temperature regime of the Pilchuck River fairly well, including diel fluctuations and periods of erratic temperature change (i.e. storm events).

(suggest moving info on Temp calibration below here)

Commented [nlm22]: note

Estimating Productivity, Respiration, Reaeration, and SOD using RMA

Put here or leave in main report?

Commented [NE(23]: (Incomplete)

Calibration of pH, nutrient, bottom algae, and other water quality parameters

By calibrating for light extinction first (depth, ISS, and chlorophyll a), a more accurate calibration of nutrient limitation is likely. Therefore, Ecology began calibration of water quality parameters by calibrating ISS and chlorophyll a in the water column. In a lotic, oligotrophic system such as the Pilchuck River, these parameters typically do not have much direct influence on productivity, however they can have a significant effect on light extinction in the water column.

Commented [NE(24]: I thought this sentence would help reader understand where you're heading from the outset

Commented [NE(25]: define

For both ISS and Chlorophyll a, the model suggested an unaccounted for source. At moderate to low settling rates, these parameters decreased downstream and failed to match observed data in the lower river. A significant load of ISS was added to the diffuse inputs to the model in order to match observed downstream data (Figure E-9). For Chlorophyll a, a large increase was observed between river mile 21.5 and 15, so a concentrated input was added within this reach (Figure E-10). The results of these modifications matched observed data well and allowed for more accurate depiction of light extinction. The effect of these loads on other important parameters was negligible (see sensitivity analysis).

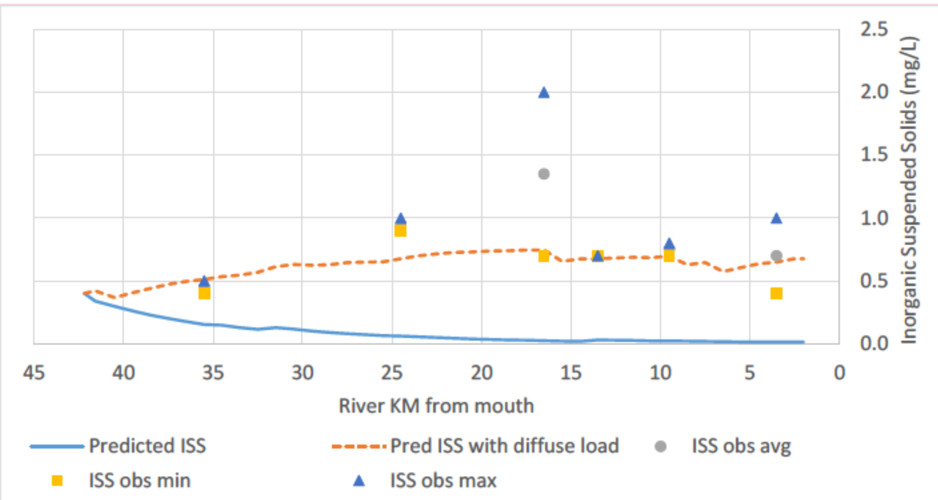


Figure E-9. Model predicted inorganic suspended solids with and without diffuse load.

Commented [NE(26]: Consider expanding label "Predicted ISS" to explain that this is without diffuse load?

Commented [NE(27]: refer to figure in text

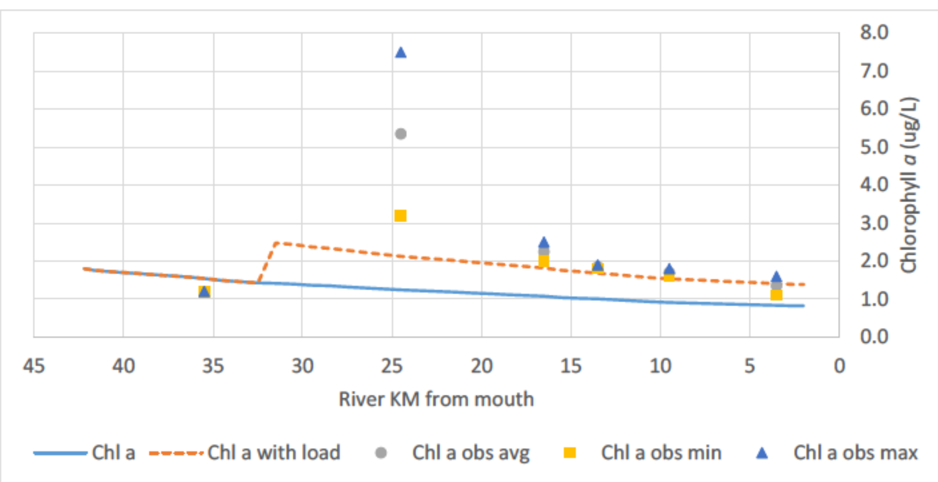


Figure E-10. Model predicted Chlorophyll a with and without concentrated load.

Commented [NE(28]: refer to figure in text

After calibrating to observed solids and chlorophyll data, Ecology began calibrating the model for pH, DO, nutrients, and bottom algae. Ecology used compiled rate sets from 29 calibrated

QUAL2Kw models developed throughout the Western U.S (Tables E-7 to E-148) to guide parameterization. These models were all developed for TMDLs by, or for, state agencies including:

- Washington State Department of Ecology (Carroll et al, 2006; Mohamedali and Lee 2008; Sargeant et al, 2006; Snouwaert and Stuart, 2015).
- Oregon Department of Environmental Quality (DEQ) (Turner et al, 2006).
- Utah DEQ (Neilson et al, 2014).
- Montana DEQ (Flynn and Suplee, 2011)
- California Regional Water Quality Board (Butkus, 2011; Tetra Tech, 2009).

Commented [NE(29)]: E-7 and E-8?

Commented [NE(30)]: Needs reference

Table E-7. Statistics for select parameters from calibrated QUAL2Kw models in the Western U.S.

Parameter	*n*	*Min*	*25th Percentile*	*Median*	*75th Percentile*	*Max*
Stoichiometry						
Carbon	20	28.5	40	40	40	70
Nitrogen	20	2.8	7.2	7.2	7.2	10
Phosphorus	20	0.4	1	1	1	1
Dry weight	20	100	100	100	100	107
Chlorophyll	20	0.3	0.5	1	1	3
Inorganic suspended solids						
Settling velocity	28	0.000001	0.2	0.59344	1.01974	2
Slow CBOD						
Hydrolysis rate	26	0	0.1	0.365	1.10032	3.9988
Oxidation rate	11	0	0.065	0.2	0.549855	3.57425
Fast CBOD						
Oxidation rate	20	0	0.35	2.7121	4	6
Organic N						
Hydrolysis	29	0.001	0.1	0.25	0.6	3.8998
Settling velocity	20	0	0.09271	0.16743	0.2225	1.8312
Ammonium						
Nitrification	29	0.01	0.93	2.5	4	10
Nitrate						
Denitrification	29	0	0.44	1	1.01	1.94
Sed denitrification transfer	29	0	0	0.1	0.6	0.99
Organic P						
Hydrolysis	29	0.001	0.11	0.25	1.5	4.21255
Settling velocity	21	0	0.08	0.11	0.5	1.84958
Inorganic P						
Settling velocity	21	0	0.08802	1.26	1.80012	2
Sed P oxygen attenuation	22	0	0.202685	1.01094	1.40852	2
Detritus (POM)						
Dissolution rate	29	0.001	0.5	1.58	3	5
Settling velocity	27	0	0.108375	0.42	0.860875	1.95865

Table E-8. Statistics for select bottom algae parameters from calibrated QUAL2Kw models in the Western U.S.

Parameter	*n*	*Min*	*25th Percentile*	*Median*	*75th Percentile*	*Max*
Bottom Algae:						
Max Growth rate	26	8.6	12.1	25.6	49.7	161.1
Basal respiration rate	26	0.0068	0.1	0.2	0.4651	1.2
Photo-respiration rate parameter	9	0.01	0.01	0.01	0.01	0.39
Excretion rate	25	0	0.07	0.2037	0.3439	0.4816
Death rate	26	0.001	0.0775	0.2582	0.5	4.46
External N half sat constant	26	15	185.5	300	342.5	493.2
External P half sat constant	26	10	52.9	67.5	100	178
Inorganic C half sat constant	25	0	1.30E-05	3.10E-05	9.00E-05	1.30E-04
Light constant	26	1.69	50	56	70.3	100
Ammonia preference	26	1.2	15.25	22.75	25	80.96
Subsistence quota for N	25	0.7	1	7.2	24.1	72
Subsistence quota for P	25	0.1	0.1285	1	4.66	10
Maximum uptake rate for N	25	28	360	500	750	1405
Maximum uptake rate for P	25	4	50	100	145	232
Internal N half sat ratio	25	0.9	1.2	2.04	3.68	9
Internal P half sat ratio	25	0.13	1.3	1.4	3.42	5

Ecology inserted the 25th and 75th percentile values into the Pilchuck River QUAL2Kw model as ranges for calibration. Ecology performed manual calibration by iteratively adjusting one rate and comparing improvements in fit mathematically and visually. Calibration started with bottom algae biomass and primary productivity. Calibration to this point suggested an additional sink for DO, which was supported by the estimates of sediment oxygen demand (SOD) derived from the RMA results.

Commented [NE(31]: New paragraph?

Calibration then focused on sediment oxygen demand from heterotrophic biofilm in the hyporheic zone. In order to generate the necessary amount of SOD and match observed organic carbon levels in the river, a source of cBOD (20 mg/L) was added to the diffuse/groundwater inflow to the model. Organic carbon and cBOD was not measured in groundwater for the study, so this value is unknown. The additional source of carbon fueling heterotrophic productivity in the sediments is unknown but could reasonably be contributed by some combination of groundwater (particularly from off stream wetlands), buried particular organic matter from storm events during the winter/spring, or settling organic matter during the model period (QUAL2Kw does not account for this). The effect of SOD and carbon loading is discussed further in the sensitivity analysis.

Tables E-9 through E-11 contain the calibrated rate parameters used in the 2012 model.

Table E-9. Calibrated (non-default) parameters in the 'Rates' worksheet for the QUAL2Kw model.

Commented [NE(32]: Needs reference in text

Parameter	*Value*	*Units*	*Symbol*
Stoichiometry:			
Carbon	40	gC	gC
Nitrogen	7.2	gN	gN
Phosphorus	1	gP	gP
Dry weight	100	gD	gD
Chlorophyll	1	gA	gA
Inorganic suspended solids:			
Settling velocity	1	m/d	v_i
Oxygen:			
Reaeration model	User model		
User reaeration model parameter A	3		
User reaeration model parameter B	0.5		
User reaeration model parameter C	-1.5		
O2 for carbon oxidation	3.08	gO2/gC	r_{oc}
O2 for NH4 nitrification	4.57	gO2/gN	r_{on}
Slow CBOD:			
Hydrolysis rate	1	/d	k_{hc}
Oxidation rate	.08	/d	k_{dcs}
Fast CBOD:			
Oxidation rate	0.08	/d	k_{dc}
Organic N:			
Hydrolysis	0.1	/d	k_{hn}
Settling velocity	0.5	m/d	v_{on}
Ammonium:			
Nitrification	2	/d	k_{na}
Nitrate:			
Denitrification	2	/d	k_{dn}
Sediment denitrification transfer coefficient	0.02	m/d	v_{di}
Organic P:			
Hydrolysis	0.1	/d	k_{hp}
Settling velocity	0.5	m/d	v_{op}
Inorganic P:			
Settling velocity	0.5	m/d	v_{ip}
Sediment P oxygen attenuation half sat constant	1.57	mgO$_2$/L	k_{spi}

Table E-10. Calibrated bottom algae parameters in the 'Rates' worksheet for the QUAL2Kw model.

Parameter	*Value*	*Units*	*Symbol*
Bottom Plants:			
Growth model	Zero-order		
Max Growth rate	17	$gD/m^2/d$ or /d	C_{gb}
Temp correction	1.025		q_{gb}
First-order model carrying capacity	100	gD/m^2	$a_{b,max}$
Basal respiration rate	0.5	/d	k_{r1b}
Photo-respiration rate parameter	0.389	unitless	k_{r2b}
Temp correction	1.04		q_{rb}
Excretion rate	0.1	/d	k_{eb}
Temp correction	1.07		q_{db}
Death rate	0.25	/d	k_{db}
Temp correction	1		q_{db}
Scour function	Flow		
Coefficient of scour function	0.1	/d/cms or /d/mps	*cdet*
Exponent of scour function	0.1		*ddet*
Minimal biomass after scour event	1.2	gD/m^2	*X0*
Catastrophic scour rate during flood event	20	/d	*Kcat*
Critical flow or vel for catastrophic scour	36	cms or m/s	*Qcrit*
External nitrogen half sat constant	180	ugN/L	k_{sNb}
External phosphorus half sat constant	25	ugP/L	k_{sPb}
Inorganic carbon half sat constant	1.30E-04	moles/L	k_{sCb}
Bottom algae use HCO3- as substrate	Yes		
Light model	Smith		
Light constant	75	langleys/d	K_{Lb}
Ammonia preference	5	ugN/L	k_{hnxb}
Nutrient limitation model for N and P	Minimum		
Subsistence quota for nitrogen	3.6	mgN/gD	q_{0N}
Subsistence quota for phosphorus	0.5	mgP/gD	q_{0P}
Maximum uptake rate for nitrogen	108	mgN/gD/d	r_{mN}
Maximum uptake rate for phosphorus	15	mgP/gD/d	r_{mP}
Internal nitrogen half sat ratio	1.1		$K_{qN,ratio}$
Internal phosphorus half sat ratio	1.1		$K_{qP,ratio}$
Nitrogen uptake water column fraction	1		$N_{UpWCfrac}$
Phosphorus uptake water column fraction	1		$P_{UpWCfrac}$

Table E-11. Calibrated hyporheic metabolism parameters in the 'Rates' worksheet for the QUAL2Kw model.

Parameter	*Value*	*Units*	*Symbol*
Detritus (POM):			
Dissolution rate	0.5	/d	k_{dt}
Temp correction	1.07		q_{dt}
Settling velocity	1	m/d	v_{dt}
pH:			
Partial pressure of carbon dioxide	391	ppm	p_{CO2}
Hyporheic metabolism			
Model for biofilm oxidation of fast CBOD	Zero-order		*level 1*
Max biofilm growth rate	1.9	gO2/m^2/d or /d	"
Temp correction	1.07		"
Fast CBOD half-saturation	1.5	mgO2/L	"
Oxygen inhib model	Half saturation		"
Oxygen inhib parameter	0.60	mgO2/L	"
Respiration rate	0.5	/d	*level 2*
Temp correction	1.07		"
Death rate	0.05	/d	"
Temp correction	1.07		"
External nitrogen half sat constant	15	ugN/L	"
External phosphorus half sat constant	2	ugP/L	"
Ammonia preference	5	ugN/L	"
First-order model carrying capacity	100	gD/m^2	"
Photosynthetic quotient and respiratory quotient for phytoplankton and bottom algae			
Photosynthetic quotient for NO3 vs NH4 use	1.30	dimensionless	*PQ*
Respiratory quotient	1.00	dimensionless	*RQ*

Figures E-11 and E-12 contain results for nitrogen and phosphorus from the calibrated model and field surveys. Figures E-13 and E-14 contain results for dissolved oxygen and pH from the calibrated model and associated field survey. Longitudinal profiles are shown for 8/28/12, the synoptic survey with greater productivity. Figures E-15 and E-16 illustrate diel results for dissolved oxygen and pH from the calibrated model for 8/28/12 at Reach 33 (Pilchuck River at Dubuque Rd).

Commented [NE(33]: This seems too brief a description for all these figures

Figure E-11. Dynamic model predicted phosphorus for Reach 23 compared to observed data from RM 7.6.

Commented [NE(34]: Figure E-8 is missing with no text reference

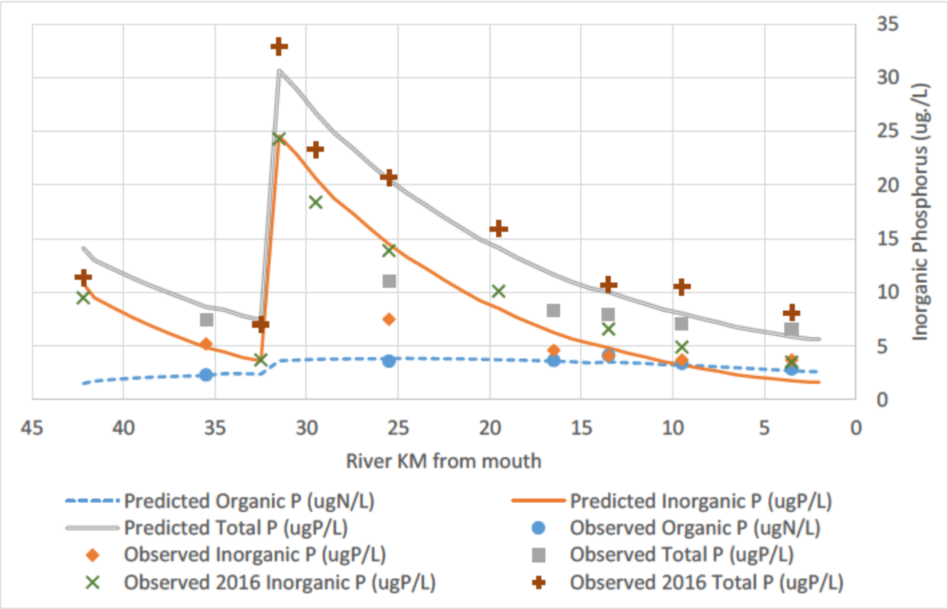


Figure E-12. Longitudinal phosphorus predictions for 8/28/12 compared to observed data.

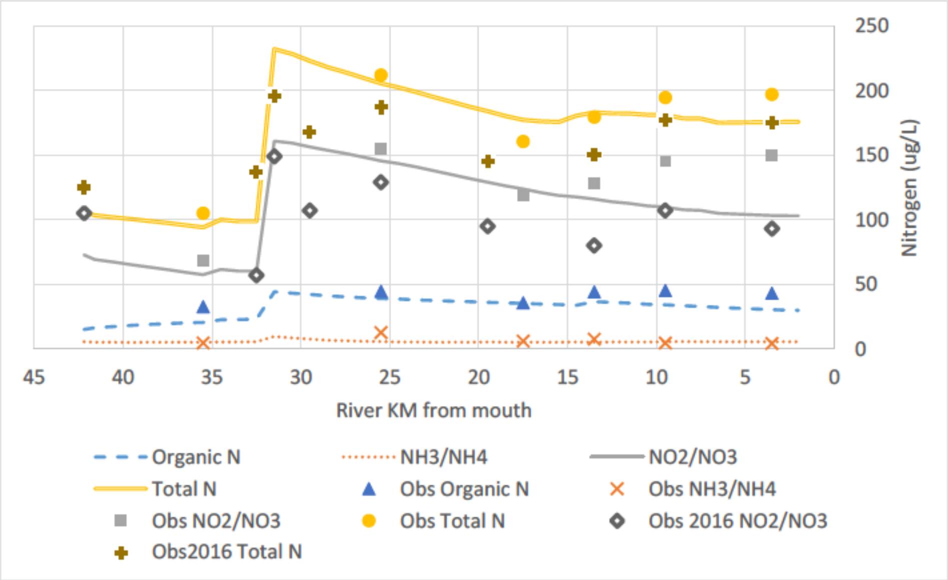


Figure E-13. Longitudinal nitrogen predictions for 8/28/12 compared to observed data.

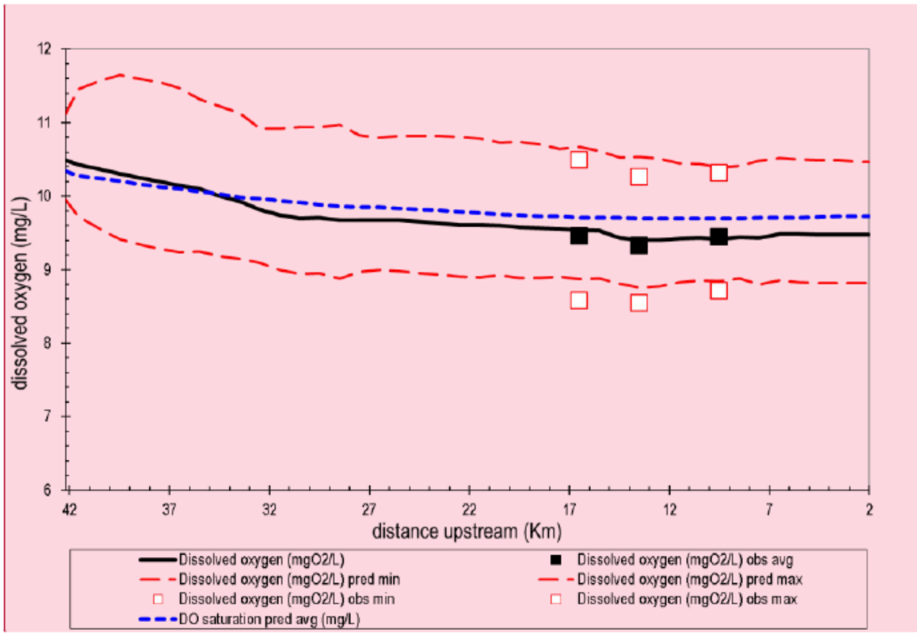
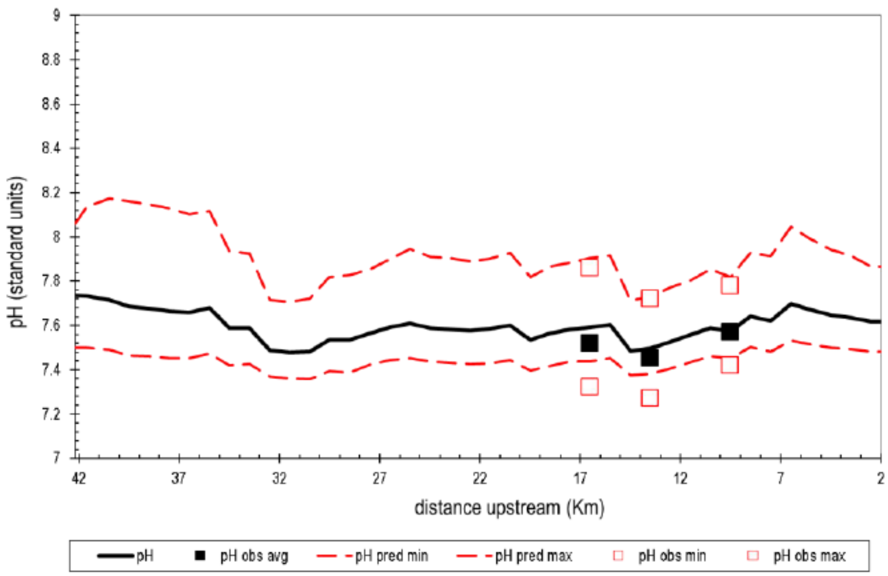


Figure E-14. Longitudinal DO predictions for 8/28/12 compared to observed data.



Commented [NE(35]: It looks like there are only 3 locations along the mainstem for calibrating DO and pH (between km 8-17)? I didn't see discussion of that, and whether you think the model is reasonably reliable for DO and pH outside that segment of the river

Figure E-15. Longitudinal pH predictions for 8/28/12 compared to observed data.

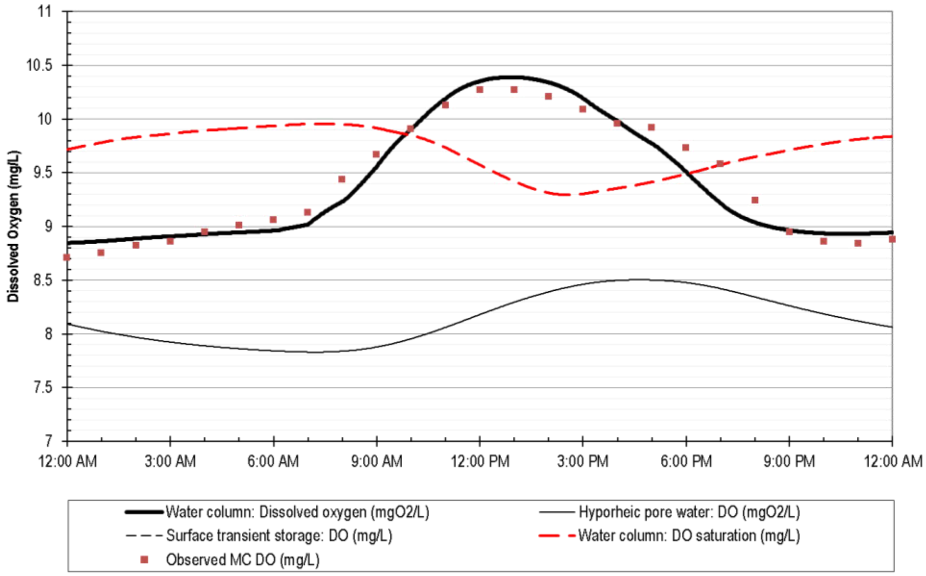


Figure E-16. Diel DO predictions for Reach 33 on 8/28/12 compared to observed data.

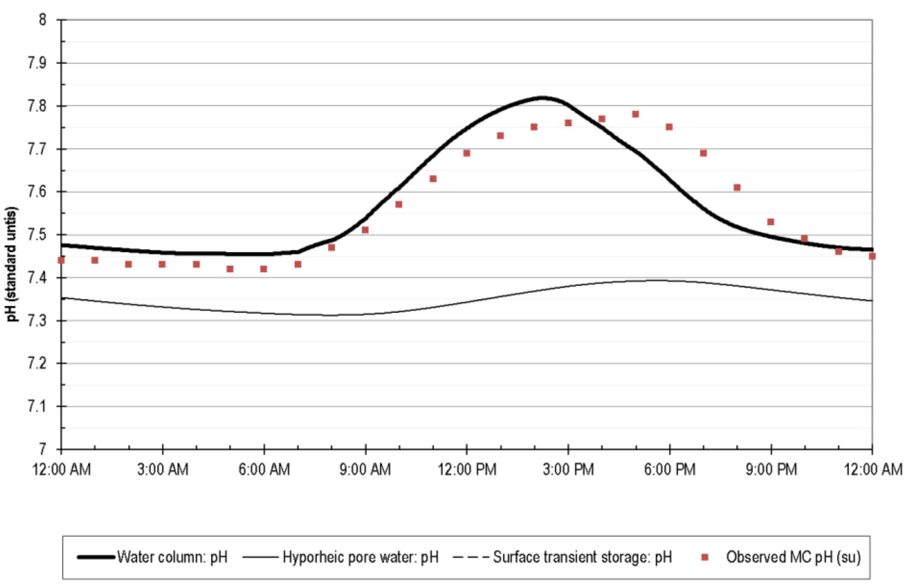


Figure E-17. Diel pH predictions for Reach 33 on 8/28/12 compared to observed data.

System Potential Temperature and DO Model

In order to evaluate the 'less than 0.2 mg/L' and 'less than 0.3°C' anthropogenic change criteria, the 2012 calibrated model was used as a starting point to develop a model simulation of system potential temperature and DO conditions. Several changes were made to the 2012 model in order to simulate system potential temperature and DO.

Boundary flow inputs

First, the headwater flows were reduced from 2012 values (7 day low flow of 56.5 cfs) to values that represent 7Q10 flow conditions (41.8). Ecology plotted the 7 day flows from the four lowest 7Day flow years from the 7Q10 analysis for USGS station 12155300, for the period of 1992-2016 (Figure E-18). Of these years, 2003 has a 26 year recurrence interval, or the lowest 7day flow on record, so it was not used to simulate critical conditions. Ecology also ruled out 2015, a 7Q13 year, because it had the lowest June/July on record.

Of the remaining years, 2004 and 2009 displayed a more typical flow pattern for this time of year and were tied as 7Q9 years (44.7 cfs). Ultimately, 2009 was selected because it had lower flows in early June. Next, two modifications were made to the 2009 flow record:

1. Daily flows were reduced by 3 cfs to achieve a 7Q10 value of 41.7 cfs.
2. The mid-August storm (flow increase) was delayed by one week, to avoid impacting the most critical days for DO (8/5/12) and 7DADmax temperature (8/11/12 – 8/17/12).

Finally, an additional source of baseflow was added back into the upstream boundary, as well as some tributaries and diffuse inputs, based on the known water rights certificates that might influence the mainstem Pilchuck flows. Only surface water rights were considered as part of this analysis. Four baseflow increase scenarios were run, based on 25, 50, 75, and 100 percent of water rights being used (Table E-10 12). Ultimately the 75 percent scenario was chosen. Although, this may represent more than current surface water use, a larger estimate accounts for some effects on groundwater baseflow from well withdrawals.

Table E-10. (add table description)

Table E-12.Estimated water rights within the Pilchuck River study area.

	# of certificates	25%	50%	75%	Full
Lower Mainstem	8	0.42	0.84	1.26	1.68
Middle Mainstem	10	0.83	1.65	2.48	3.30
Upper Mainstem	4	0.22	0.44	0.65	0.87
Upper Tribs	6	0.22	0.44	0.65	0.87
Little Pilchuck	6	0.19	0.38	0.57	0.76
Dubuque	4	0.13	0.25	0.38	0.50

Commented [NE(36]: Consider adding the modeling considerations checklist (for natural condition scenario) as a table in this appendix You probably have that checklist, but I'll go ahead and add an example copy to the review folder I think it would help the reader understand what you did and why you did it Would also help ensure completeness

One of the things on that checklist I don't see is channel morphology Maybe at least mention it even if you did not change it Also for hydrologic modification on the checklist, was there some type of a dam on this system?

I think you also described microclimate considerations for natural conditions in the main report? I'd repeat all the main report information here if that's the case, to be sure the appendix is complete

Upstream*	4	1.31	2.54	4.47	6.51
	Total (CFS)=	**3.3**	**6.5**	**10.5**	**14.5**

* Includes City of Snohomish Water Treatment Plant (WTP) where full= full water rights, 75% = WTP design capacity; 50% = WTP typical use; 25% = WTP average supply from 2003-05.

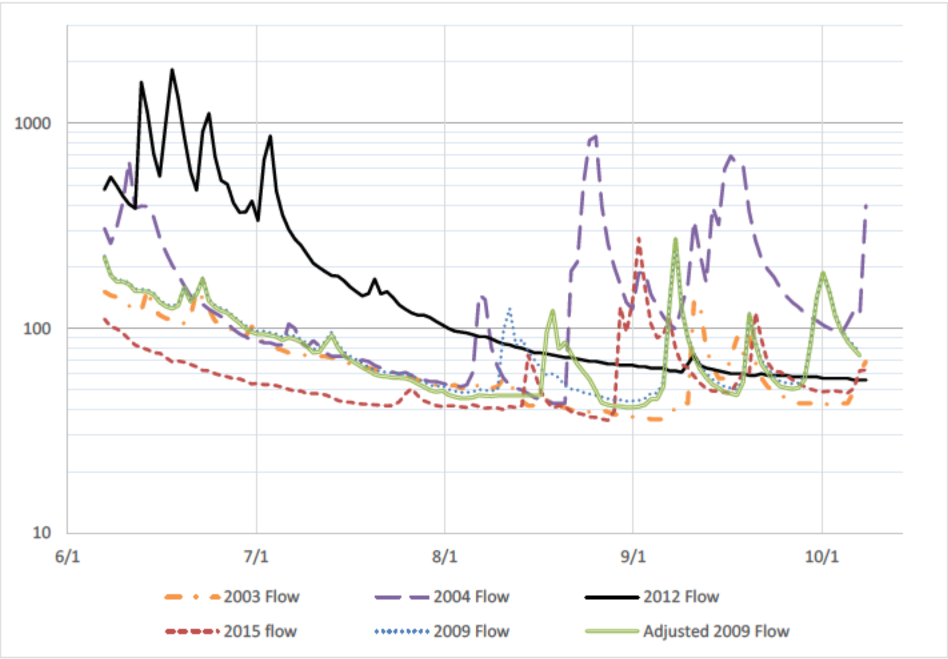


Figure E-18. Comparison of 7Q low flow years for USGS station 12098500.

Nutrient concentrations

The 2012 nutrient concentrations for the headwater boundary at Menzel Lake Road were not reduced in the natural conditions model, due to a record of low (<10 ug/L SRP) historical values and the lack of potential anthropogenic nutrient sources upstream.

Nutrient concentrations for surface water inputs (tributaries) were also not reduced in the natural conditions model. Based on the limited nutrient data available, these values were also low for phosphorus (<10 ug/L SRP).

Nutrient concentrations for groundwater inputs were set as the 25th percentile, 6.4 ug/L SRP, from the 2016 samples collected from piezometers, springs, and seeps in the study area.

Removed point source inputs

Ecology removed the flow and water quality inputs from the Granite Falls WWTP.

System potential shade

Ecology estimated historic system potential shade height by:

1. Analyzing soil types within the riparian zone.
2. Determining the dominant site index species and associated height using the Snohomish County soil survey and SSURGO database.
3. Determining a composite/average system potential vegetation height based on the soil survey site index values and percentage of the overall riparian buffer zone (TableTable E-1114). One composite SPV was used for the entire Pilchuck River, given that there was not a clear delineation of dominant soil types/species based on river reach.

Commented [NE(37]: define

Commented [NE(38]: define

To corroborate general species occurrence and heights, Ecology used:

- Descriptions of historic riparian tree species and measurements of diameters taken directly from General Land Office (GLO) field survey maps and notes of the area circa 1860-1880.
    - Diameter at breast height (DBH) measurements from the GLO field notes were converted from DBH to tree height using species specific height/DBH models developed for coastal areas of the Pacific Northwest (Hanus et al, 1999; Keyser, 2015).
- Historical analysis of GLO surveys in the Snohomish and Pilchuck River valleys from Collins (2003) of historic freshwater riparian and forested floodplain tree species frequency and basal area estimates. TableE-1213 summarizes the results applicable to the study area.

Table E-11.-13. Summary of historic tree frequency and basal area estimates for the Snohomish River valley from Collins (2003).

Species	Freshwater Riparian (n=15)		Forested Floodplain (n=129)	
	Frequency	Basal Area	Frequency	Basal Area
Red Alder	13%	3%	18%	11%
Willow spp.	40%	3%	5%	1%
Vine Maple	13%	1%	12%	1%
Black Cottonwood	13%	10%	4%	9%
Other Deciduous	0%	0%	7%	1%
Pacific Crabapple	0%	0%	7%	<1%
Big-leaf Maple	7%	35%	10%	10%
Western Redcedar	7%	20%	11%	44%
Sitka Spruce	7%	28%	19%	22%
Western Hemlock	0%	0%	5%	1%
Pacific yew	0%	0%	2%	<1%

TableE-12-. Composite system potential vegetation height based on the soil survey site index values and percentage of the overall riparian buffer zone.

Mapunit Name	% of Total Riparian Area	Dominant Species	Site index	Site index year basis	Site Index Used	Contribution to SPV height
Sultan silt loam	30.5%	Red alder	87	50	87	26.53
Pilchuck loamy sand	27.5%	Doug Fir	152 (115)	100 (50)	152	41.73
Tokul-Winston gravelly loams	6.1%	Doug Fir/W. Hemlock	173/166 (131/117)	100 (50)	169.5	10.26
Puyallup fine sandy loam	5.7%	Doug Fir/ Red Alder	173/na (115/85)	100 (50)	129	7.41
Menzel silt loam	5.1%	Doug Fir	179 (180?)	100 (50)	179	9.13
Norma loam	4.9%	Red alder	106	50	106	5.19
Puget silty clay loam	3.4%	Red alder	95	50	95	3.25
Ragnar fine sandy loam	2.9%	Doug Fir/W. Hemlock	165/159 (125/112)	100 (50)	162	4.70
Tokul-Ogarty-Rock outcrop complex	2.4%	Doug Fir/W. Hemlock	173/166 (131/117)	100 (50)	169.5	4.02
Sumas silt loam	2.3%	Red alder	80	50	80	1.88
Winston gravelly loam	2.2%	Doug Fir/W. Hemlock	167/164 (127/104)	100 (50)	165.5	3.67
Tokul gravelly medial loam	1.7%	Doug Fir/W. Hemlock	173/166 (131/117)	100 (50)	169.5	2.96
Riverwash	1.4%	n/a	n/a		0	0.00
Pits	1.2%	n/a	n/a		0	0.00
Pastik silt loam	0.8%	Doug Fir	180 (135)	100 (50)	180	1.48
Cathcart loam	0.5%	Doug Fir	175 (130)	100 (50)	175	0.85
Everett gravelly sandy loam	0.5%	Doug Fir	141 (111)	100 (50)	141	0.65
Nargar-Lynnwood complex	0.3%	Doug Fir	185/158 (138/121)	100 (50)	171.5	0.59
Sultan variant silt loam	0.2%	Red alder	85	50	85	0.18
Skykomish gravelly loam	0.1%	Western Hemlock	152 (106)	100 (50)	152	0.21
Terric Medisaprists, nearly level	0.1%	n/a	n/a		0	0.00
Kitsap silt loam	0.1%	Doug Fir	166 (123)	100 (50)	166	0.08
Sulsavar gravelly loam	0.0%	Doug Fir	183 (141)	100 (50)	183	0.06
					Composite SPV height ft =	124.8
					Composite SPV height m =	38.1

System Potential Model Assumptions

- The technical approach for estimating nutrients is an adequate representation of "natural" concentrations.
- Mature system potential riparian shade is adequately represented by a height of 38m.
- Historical groundwater flows were similar to levels estimated from the 2012 study. Similarly, the percent of river flow exchanging with the hyporheic zone and the thickness of this zone were similar to those estimated in the 2012 study.

Model evaluation - sensitivity and error analysis

Ecology evaluated the quality of the model through both quantitative and qualitative methods, including:

- Quantitative:
  - Assessing goodness of fit to observed data using RMSE.
  - Assessing the bias of the model compared to the observed data.
  - Sensitivity analysis on key rate parameters and inputs.
- Qualitative:
  - Visual comparison of observed vs predicted spatial and temporal patterns in the data.
  - Model review and consultation from two senior water quality modelers from Ecology's Environmental Assessment Program.

Error Analysis

The Pilchuck River QUAL2Kw model goodness of fit to observed data is summarized in Tables E-1215 and E-1316. The Root Mean Squared Error (RMSE) statistic expresses the magnitude of typical model error for a variable in the same units as that variable. The Root Mean Squared Error Coefficient of Variation (RMSE CV) expresses the proportion of typical model error to the typical value of the variable. The overall bias statistic expresses the tendency of the model to over- or under-predict the value of a given variable. Bias% expresses this tendency as a proportion of the typical value of the variable. The average observed values from this study for most variables are given for reference.

For most variables, RMSE and bias are calculated by comparing modeled daily average values to observed daily average or grab sample values. For variables that display a marked diel swing, such as temperature, dissolved oxygen, and pH, the RMSE and bias are calculated for daily maximums and minimums as well. RMSE CV and Bias%, which express error as a proportion of typical variable values, are given for those variables that express a quantity or concentration of something. These statistics are not appropriate for temperature or pH.

The QUAL2Kw model provides a good simulation of DO in the Pilchuck River. In particular, daily minimum DO had a minimal amount of error (RMSE = 0.23 mg/L) and bias (overall bias = +0.11 mg/L). The model also provides a good simulation of SRP concentrations, with low error (RMSE = 1.7 ug/L) and bias (+0.4 ug/L).

Table E-14. Summary statistics for goodness-of-fit of the QUAL2Kw model to observed continuous data.

	Temp-Min (degC)	Temp-Max	Temp-Mean	SpCond - Mean (uS/cm)	DO – Min (mg/L)	DO – Max	DO – Mean	pH-Min	pH-Max	pH-Mean
RMSE	0.89	0.81	0.82	5.02	0.23	0.49	0.31	0.06	0.07	0.08
Bias	-0.35	-0.22	-0.30	-3.81	0.10	0.19	0.03	0.02	-0.04	-0.05
Mean	13.14	16.74	14.82	82.53	8.71	10.14	9.39	7.39	7.78	7.58
RMSCV	0.07	0.05	0.06	0.06	0.03	0.05	0.03	0.01	0.01	0.01
Bias %	-3%	-1%	-2%	-5%	1%	2%	0%	0%	-1%	-1%

Table E-15. Summary statistics for goodness-of-fit of the QUAL2Kw model to observed discrete data.

	Bottom algae (gD/m^2)	ISS (mgD/L)	TSS (mgD/L)	Alk (mg/L)	Total N (ug/L)	NH3/4 (ug/L)	NO2/NO3 (ug /L)	SRP (ugP/L)	Total P (ugP/L)	DOC (mgD/L)
RMSE	0.85	0.69	0.80	2.90	34.10	1.61	34.18	1.73	2.49	
Bias	0.30	-0.32	0.37	2.52	3.45	0.31	6.99	0.38	0.90	
Mean	2.41	1.25	2.25	34.86	160.36	5.33	105.19	4.01	8.01	
RMSCV	0.35	0.55	0.35	0.08	0.21	0.30	0.32	0.43	0.31	
Bias %	12%	-25%	16%	7%	2%	6%	7%	10%	11%	

Error Statistics

Root-Mean-Square Error Statistic (RMSE). The RMSE (E_{rms}) is defined as

$$E_{rms} = \sqrt{\frac{\sum (O - P)^2}{n}}$$

where,
O = observation
P = model prediction at same location and time as the observation
n = number of observed-predicted pairs

Root-Mean-Square Coefficient of Variation.

$$RMSE\ CV = \frac{RMSE}{Avg\ obs\ value}$$

Mean Error Statistic. The mean error (E) or overall bias between model predictions and observations is defined as

$$E = \frac{\sum(O - P)}{n}$$

A mean error of zero is ideal. A non-zero value is an indication that the model might be biased toward either over- or under-prediction, and typically represented by either a plus or negative sign (e.g., +0.5 or -0.5).

Relative Percent Difference. The relative percent difference (%RPD) is defined as

$$RPD = \left[\frac{|P_i - O_i| * 2}{O_i + P_i}\right] * 100$$

Commented [NE(39]: Suggest presenting this earlier in the appendix under a separate sub-section

Effective Shade Error Analysis

Ecology also performed an error analysis for the shade by comparing Shade model outputs to estimates from two different methods for calculating effective shade from hemispherical photos: 1) using Hemiview software 2) using Gap Light Analyzer (GLA) software (Table E-1417). Comparisons were made for effective shade on August 14th during critical period for temperature. GLA effective shade showed slightly better agreement with the shade model, which may be in part related to the fact that Hemiview does not include diffuse radiation for daily calculations or the differences in the solar model and parameterization used for each. GLA documentation has recommended solar model parameters for varying conditions based on regionally relevant data collected in Victoria, British Columbia (reference needed).

Table E-14-16. Comparison of Shade model effective shade to GLA and Hemiview software outputs.

Site	Shade.xls	Hemiview	GLA	Hemiview – Shade.xls	GLA – Shade.xls
PIL25	53.7%	62.2%	54.1%	8.5%	0.3%
PIL21.5	26.4%	19.9%	25.7%	-6.5%	-0.7%
PIL15	34.1%	56.8%	51.9%	22.7%	17.7%
PIL10	19.4%	15.9%	12.7%	-3.5%	-6.6%
PIL8.5	34.1%	53.4%	51.7%	19.3%	17.6%
PIL5.7	33.3%	54.4%	41.8%	21.1%	8.5%
PIL2	33.5%	24.7%	33.9%	-8.9%	0.4%
			Bias =	7.54%	5.31%
			RMSE =	15%	10%

Temperature Error Analysis (combine with above)

The average temperature RMSE for all evaluated reaches, for the entire 124 day model period, was 0.91°C and the average bias was -0.42°C (Table E-1518). Results of other modeling efforts suggest this would generally be considered an acceptable level of model skill for this type of application (Sanderson and Pickett, 2014). The average RMSE for all evaluated reaches, for 7/8/12 to 9/8/12 (period of warmest temperatures), was 0.64°C and the average bias was -0.11°C (Table E-19; Figure E-19). The significant improvement in model fitness for this period was likely related to the fact that the majority of the input data was collected in the months of July and August and the fact that the model was calibrated to critical low-flow, warmer temperature conditions.

Table E-17. Error statistics for temperature in the QUAL2Kw model from 6/8/12 to 10/8/12.

		Hourly Temp		7DAD Max Temp	
Reach	~RM	RMSE	BIAS	RMSE	BIAS
	21.5	0.73	-0.11	0.54	0.00
	15.1	0.93	-0.56	0.76	-0.57
	10.4	1.00	-0.77	1.11	-0.97
	8.5	0.94	0.18	0.65	0.19
	5.7	0.89	-0.53	0.60	-0.35
	2.0	0.96	-0.73	0.79	-0.48
Average =		**0.91**	**-0.42**	**0.74**	**-0.36**

Table E-18. Error statistics for temperature in the QUAL2Kw model from 7/8/12 to 9/8/12.

		Hourly Temp °C		7DAD Max Temp °C	
Reach	~RM	RMSE	BIAS	RMSE	BIAS
	21.5	0.72	-0.10	0.46	0.16
	15.1	0.66	-0.10	0.4	-0.17
	10.4	0.65	-0.36	0.67	-0.55
	8.5	0.74	0.35	0.54	0.38
	5.7	0.56	-0.06	0.28	0.03
	2.0	0.57	-0.31	0.39	0.04
Average =		**0.65**	**-0.10**	**0.46**	**-0.02**

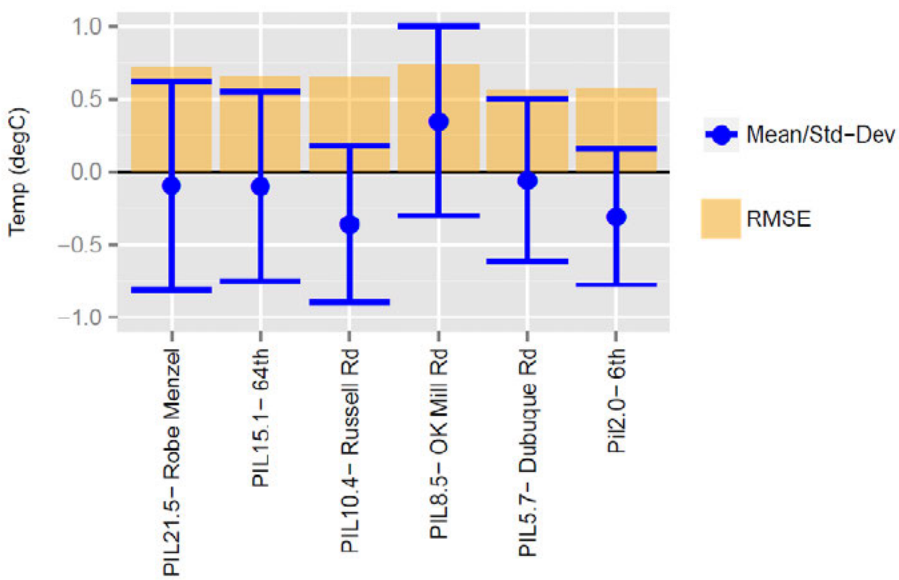


Figure E-19. Error statistics for temperature in the QUAL2Kw model from 7/8/12 to 9/8/12.

Sensitivity Analysis

In order to analyze the sensitivity of individual parameter estimates for the calibrated QUAL2Kw model, Ecology perturbed one parameter at a time. First the parameter was set to the 25th percentile of the auto-calibration range (low) and then set to the 75th percentile (high) (see Table E-7 in *Model calibration*). If the calibrated model parameter value was set at the high or low end of the perturbed range, then the model parameter was only altered for the opposite end of the range.

Sensitivity was evaluated by recalculating the RMSE between simulated and observed values, or goodness of fit, (as described in *Error Analysis*) after each parameter was perturbed.

Ecology evaluated the sensitivity in goodness of fit for six key model metrics: daily min DO, daily max DO, inorganic phosphorus, nitrate-nitrite, bottom algae biomass, and daily max pH based on the low and high variations (Figures E-20 to E-24). The baseline RMSE represents the calibrated model fitness, while the low and high end RMSE values show how each parameter change would affect model fitness.

Commented [NE(40]: Why was temperature sensitivity not included? Seems like you should include some kind of temperature sensitivity analysis

Additional information:

- For the QUAL2Kw bottom algae parameters:
    - The scour function sensitivity was tested by turning the function off. The scour function is based on terms for periphyton detachment and catastrophic loss of biomass determined in the model developed by Uehlinger et al. (1996).
    - Bottom Algae “use HCO3- as substrate” option sensitivity was tested by changing from ‘Yes’ (calibrated) to ‘No’
    - Ecology used the half-saturation light extinction model in the calibrated model. Only the light model constant was adjusted. Other extinction models were not tested for sensitivity.
- For QUAL2Kw hyporheic biofilm parameters:
    - The Fast CBOD oxidation model sensitivity was tested by changing from zero-order (calibrated) to first-order.
    - Hyporheic flow sensitivity was tested by changing the calibrated values for zone depth from 20-60 cm to 100cm and flow fraction from 10-15% to 25%.

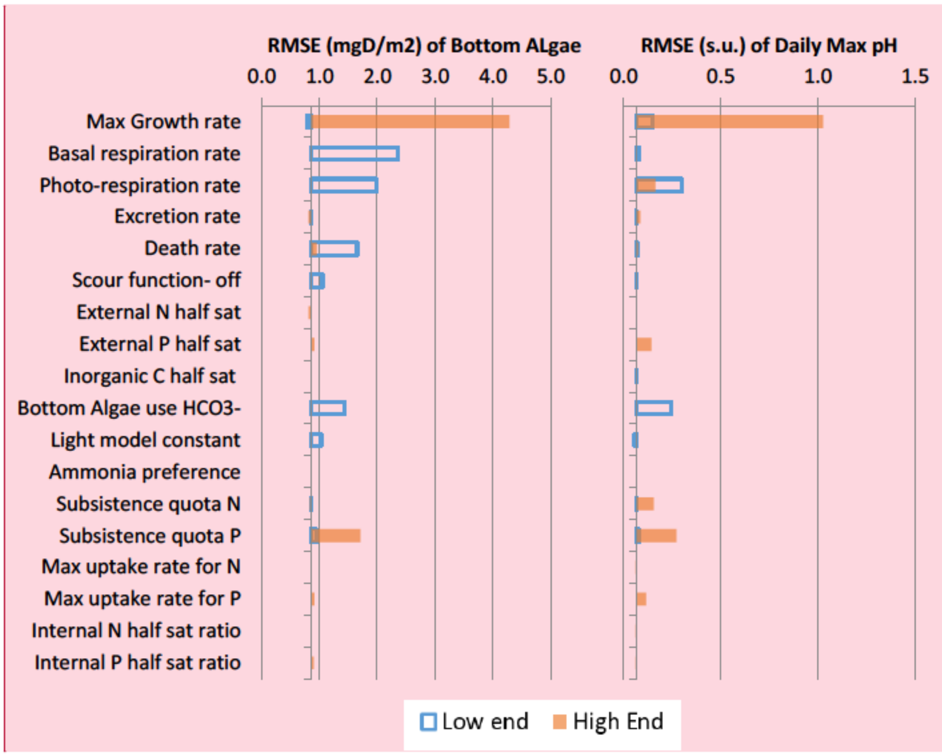
Results of the sensitivity analysis showed:

- For bottom algae parameters,
    - DO, bottom algae biomass, and max pH goodness of fit were all significantly negatively impacted by a higher maximum growth rate. They were also negatively impacted by lower respiration rates (Figures E-20 & E-21). These results illustrate why the calibrated model used a lower maximum growth rate and higher respiration rates. This agrees with evidence that the Pilchuck River is likely a relatively low primary productivity stream, which is evident from:
        - The relatively low algal biomass levels,
        - Relatively low nutrient levels,
        - Predominance of diatoms over green algae, and
        - Estimate of respiration being greater than gross primary productivity.
    - SRP concentration in the river was, predictably, most sensitive to max growth rate and the kinetic phosphorus rates. Kinetic phosphorus rates are affected by the following model parameters: external half saturation constant, subsistence quota, max uptake rate, and internal half sat ratio.
    - NO2-NO3 concentration in the river was, predictably, most sensitive to max growth rate and the kinetic nitrogen rates. Kinetic nitrogen rates are affected by the following model parameters: internal half sat ratio, subsistence quota, and max uptake rate.
    - The Pilchuck River calibrated growth rate (17 $gD/m^2/d$) was similar to the median growth rate of the 27 QUAL2Kw models (25 $gD/m^2/d$) with zero-order growth rates (interquartile range of 12 to 50 $gD/m^2/d$; see Table E-7 in *Model calibration*).
- For hyporheic biofilm parameters,

- DO model fitness was most negatively impacted by a higher max growth rate, the removal of hyporheic flow, and switching from the zero-order to the first-order fast CBOD oxidation model (Figure E-22). A first-order model assumes growth is limited by surface area space, where a zero-order assumes organisms can grow on top of each other.
  - These results suggest that limiting primary productivity growth and including heterotrophic growth in the hyporheic zone are important to the model calibration
  - The RMA analysis and initial model concluded that a significant source of oxygen demand was likely coming from the sediment or hyporheic zone. Oxygen demand from the hyporheic zone made the most sense given the significant amount of hyporheic activity observed in the field and the coarse substrates.

Commented [NE(41]: This surprises me a bit, could you explain to the reader? The model includes heterotrophic organisms in the hyporheic zone?

Commented [nlm42R41]: Yes… Guess I should do a better job of explaining that elsewhere!



Commented [NE(43]:
Cool figures!

I'm unsure of the units of bottom algae I'm expecting to see biomass (maybe g/m^2), but it looks like (mg day / m^2), is this correct?

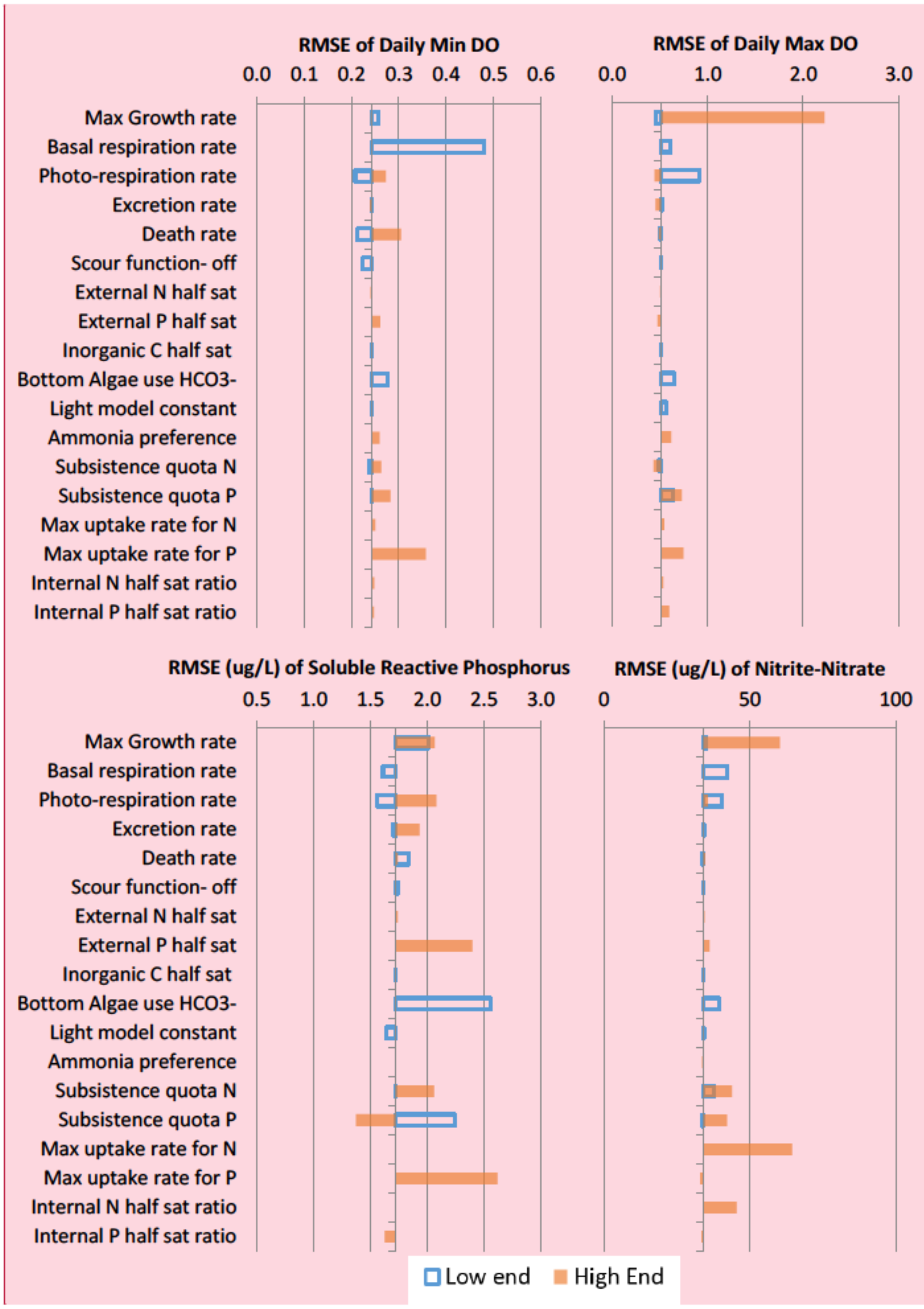
Maybe include the word "biomass" in the axis label

Why is the RMSE baseline for pH near 0 1? Is that the RMSE of the calibrated model vs observed data? Please explain to the reader what the baseline RMSE value means here So, relative to the baseline RMSE, the perturbed scenarios either achieved a better fit or a worse fit?

These are great for showing which parameters are most sensitive, but it's hard to translate into what it means for the river or your calibrated model In other words, would it be helpful to show how bias was affected by these changes as well? [Did pH go up or down due to the change? Did DO-min?] Maybe that's ok, just to say what parameters are the most sensitive and not really go into details about the direction things would change?

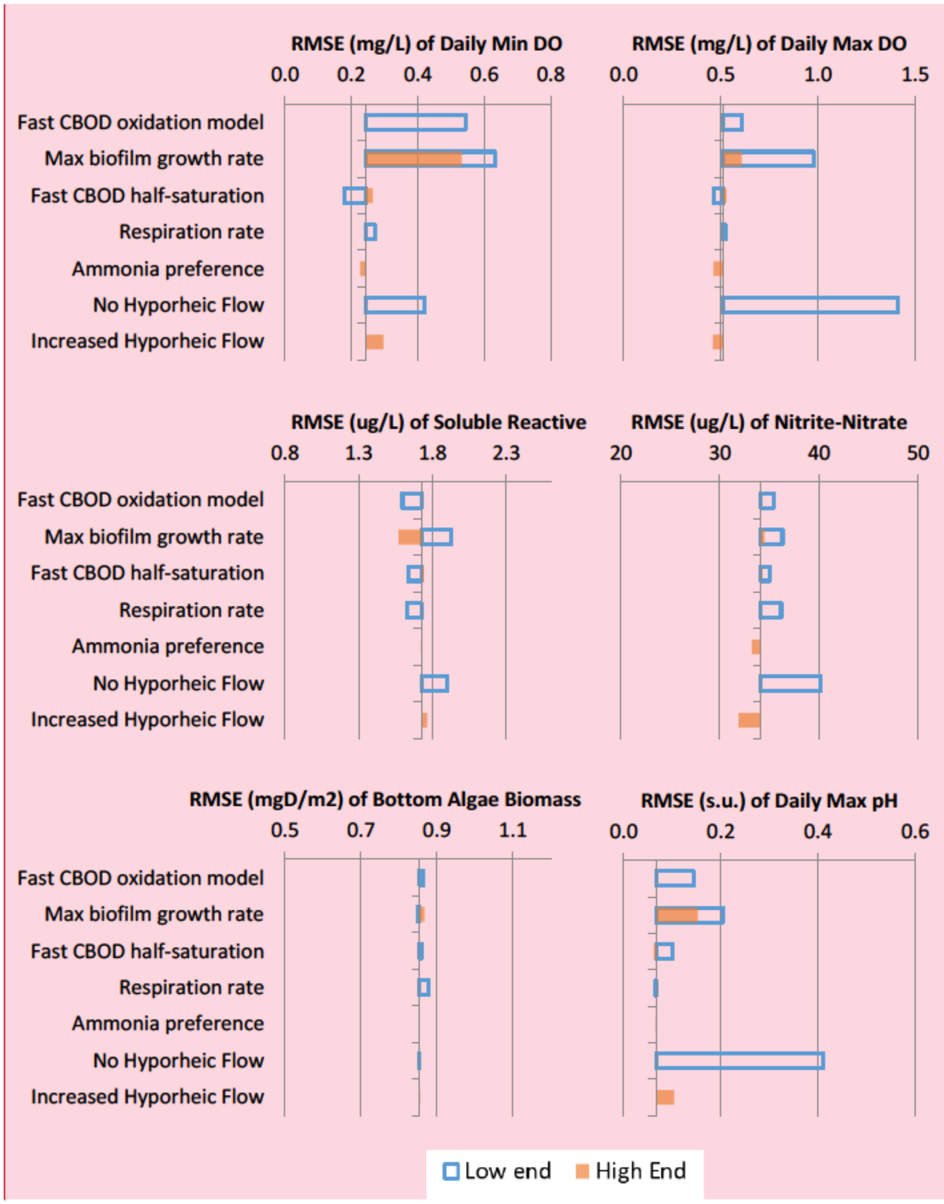
On the other hand, these plots appear to imply an increase or decrease in the river pH, but I don't think that's what you're saying You're saying that the goodness of fit increased or decreased For example, an increase in RMSE for pH could be caused by pH going lower The possibility exists for reader confusion

Figure E-20. Sensitivity (RMSE) of bottom algae biomass and daily max pH goodness of fit to variations in bottom algae parameters.



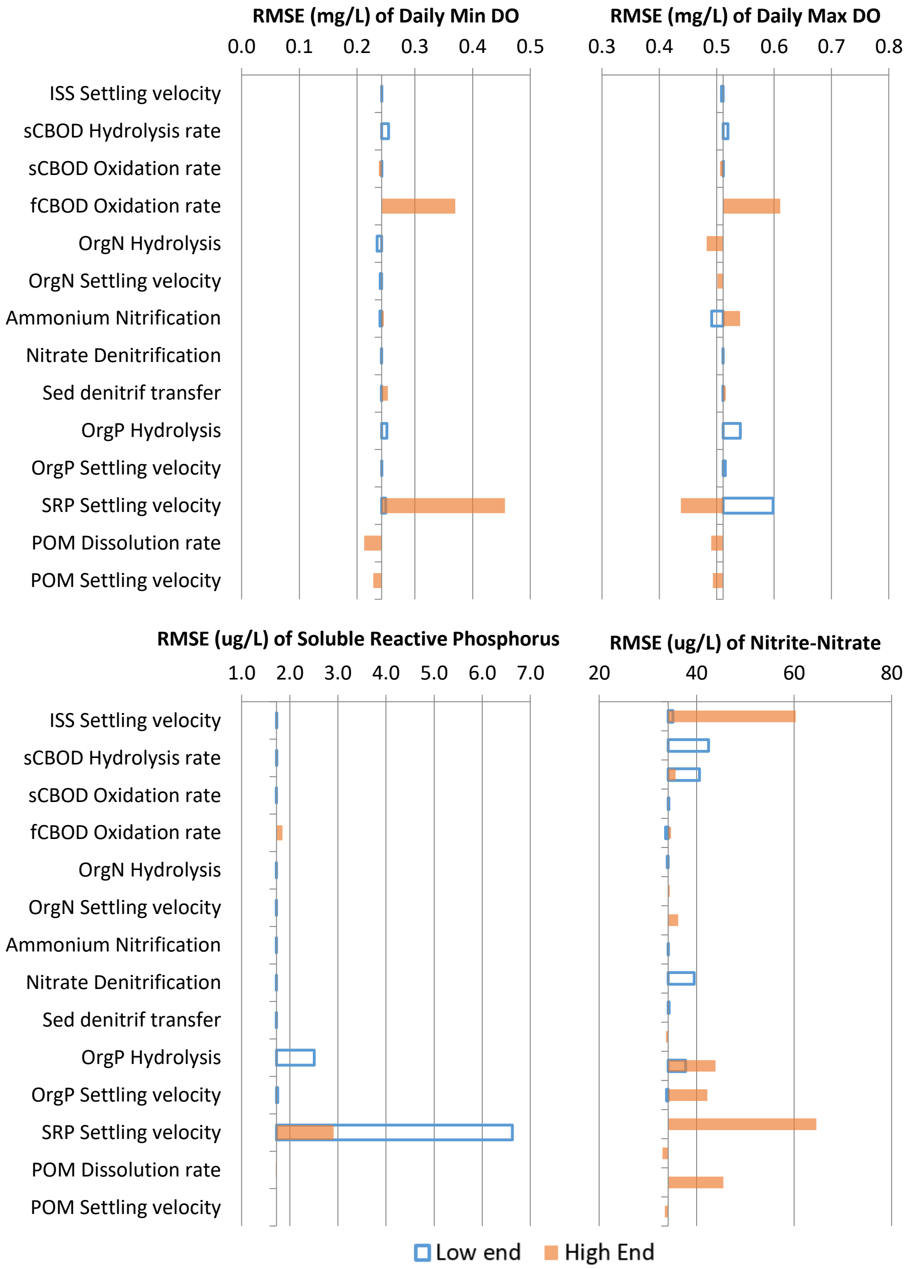
Commented [NE(44]: DO needs units of measurement

Figure E-20. Sensitivity (RMSE) of dissolved oxygen, soluble reactive phosphorus, and nitrite-nitrate goodness of fit to variations in bottom algae parameters



FigureE-19-. Sensitivity (RMSE) of dissolved oxygen, soluble reactive phosphorus, nitrite-nitrate, bottom algae biomass, and daily max pH goodness of fit to variations in hyporheic parameters and inputs.

Commented [NE(45]: Phosphorus is omitted from middle left label



RMSE (mg/L) of Daily Min DO
0.0 0.1 0.2 0.3 0.4 0.5
RMSE (mg/L) of Daily Max DO
0.3 0.4 0.5 0.6 0.7 0.8
ISS Settling velocity
sCBOD Hydrolysis rate
sCBOD Oxidation rate
fCBOD Oxidation rate
OrgN Hydrolysis
OrgN Settling velocity
Ammonium Nitrification
Nitrate Denitrification
Sed denitrif transfer
OrgP Hydrolysis
OrgP Settling velocity
SRP Settling velocity
POM Dissolution rate
POM Settling velocity
RMSE (ug/L) of Soluble Reactive Phosphorus
1.0 2.0 3.0 4.0 5.0 6.0 7.0
RMSE (ug/L) of Nitrite-Nitrate
20 40 60 80
ISS Settling velocity
sCBOD Hydrolysis rate
sCBOD Oxidation rate
fCBOD Oxidation rate
OrgN Hydrolysis
OrgN Settling velocity
Ammonium Nitrification
Nitrate Denitrification
Sed denitrif transfer
OrgP Hydrolysis
OrgP Settling velocity
SRP Settling velocity
POM Dissolution rate
POM Settling velocity
Low end
High End

Figure E-20-21. Sensitivity of dissolved oxygen, soluble reactive phosphorus, and nitrite-nitrate goodness of fit to variations in nutrient and settling parameters.

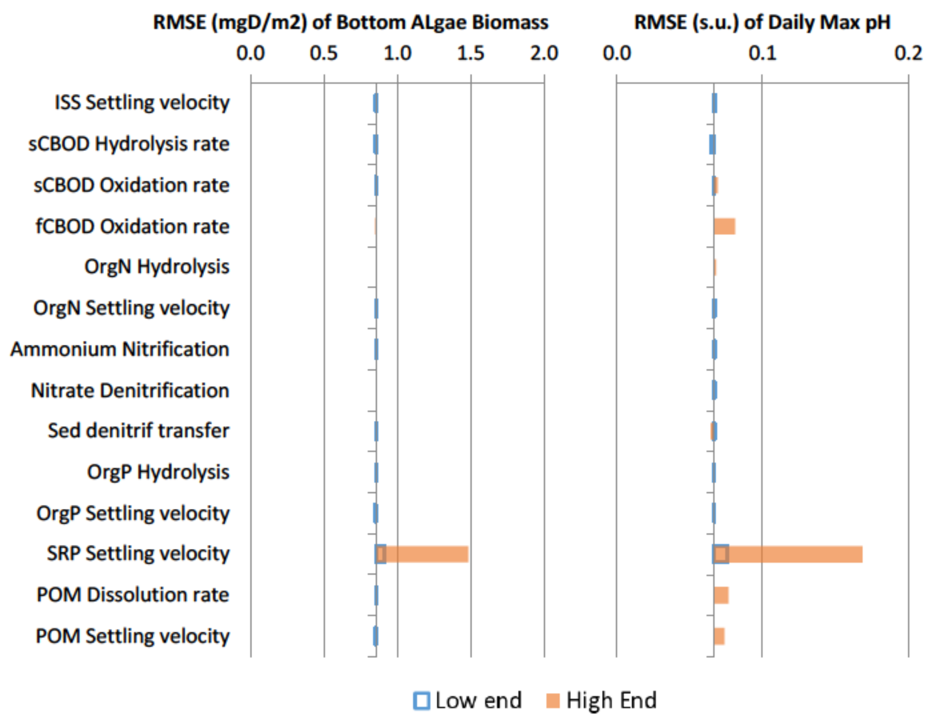


Figure E-22. Sensitivity of bottom algae biomass and max pH goodness of fit to variations in nutrient and settling parameters.

Model Sensitivity to Nutrient Limitation

Ecology also tested the sensitivity of bottom algae growth limitation and growth saturation to concentrations of inorganic phosphorus and nitrogen in the river. This was accomplished by setting one nutrient artificially very high (well above saturation) and the other nutrient at zero (limiting nutrient) at the upstream boundary. The concentration of the limiting nutrient was then gradually increased both downstream and over time to create a large gradient of nutrient concentrations and bottom algae growth in the river.

Model outputs for growth limitation and nutrient concentration were then plotted for July and August at noon (Figures E-25 and E-26), to represent peak primary productivity. 90 percent growth saturation was reached at an inorganic phosphorus concentration of ~9.7 ug/L and dissolved inorganic nitrogen of ~59 ug/L. These values are within the literature range for diatom

Commented [NE(46]: In the figure, the curve appears to have 90% growth limitation as an asymptote So at 9 7 ug/L, it looks like it's still below 80% Please explain to the reader growth saturation in rivers and streams for phosphorus of 3 ug/L (Bothwell, 1985) and 23 ug/L (Rier and Stevenson, 2006). For nitrogen, only one known estimate is available from the literature, 86 ug/L (Rier and Stevenson, 2006).

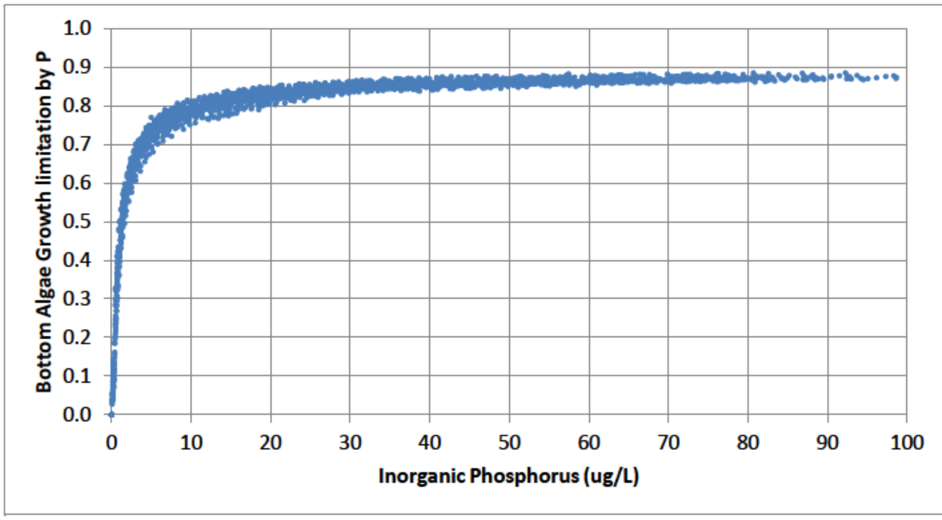


Figure 23 Growth limitation and saturation sensitivity tests for inorganic phosphorus.

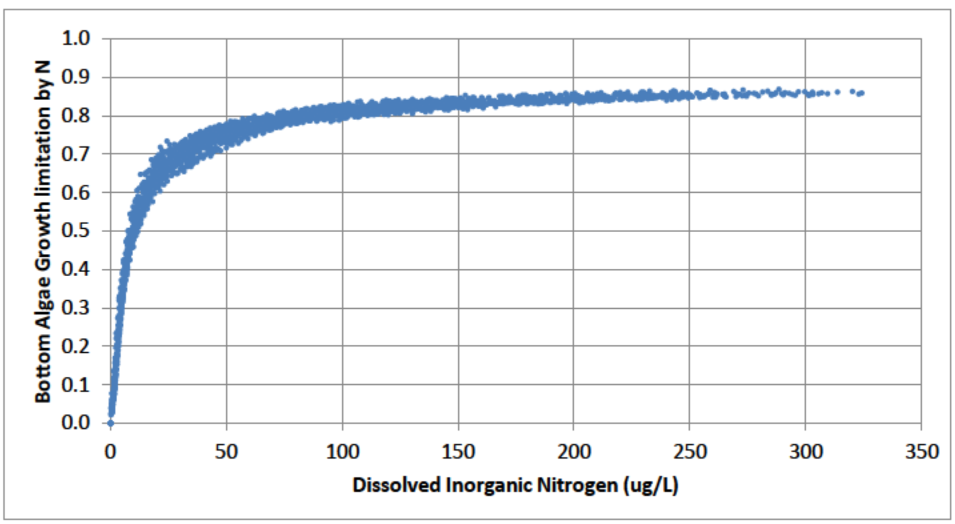


Figure 24 Growth limitation and saturation sensitivity tests for dissolved inorganic nitrogen.

Commented [NE(47]: My brain is scrambled

Wouldn't 0 0 growth limitation mean that no limitation is occurring? But that's obviously not the case on this figure

And why doesn't it ever reach 1 0? It seems like the algae would eventually be happy with the phosphorus level! Spoiled algae!

Uncertainty Analysis

Finally, Ecology evaluated the uncertainty associated with using the model to evaluate management scenarios by comparing the temperature and DO outputs from the existing (calibrated 2012) and system potential models. Assuming that the system potential coefficient of variation (CV) is equal to that of the existing conditions, the RMSE between the existing and system potential scenarios can be calculated using the existing model RMSE and the coefficient of determination for the simple linear regression (R^2) between the two scenarios (Figure E-26). The RMSE between scenarios was estimated to be 0.16°C for temperature and 0.08 mg/L for DO (Table E-20). This provides an estimate of uncertainty between the two models.

Commented [NE(48]: I don't understand this Why would the CV be equal between the calibrated 2012 model and the system potential (natural conditions) model after all the changes?

Table E-19. Variance and RMSE between modeling scenarios.

Parameter	RMSE	Coefficient of Determination for linear regression (R^2)	Variance between scenarios	RMSE between scenarios
Temp	0.65 °C	0.97	0.02535	0.16 °C
DO	0.23 mg/L	0.94	0.006577	0.08 mg/L

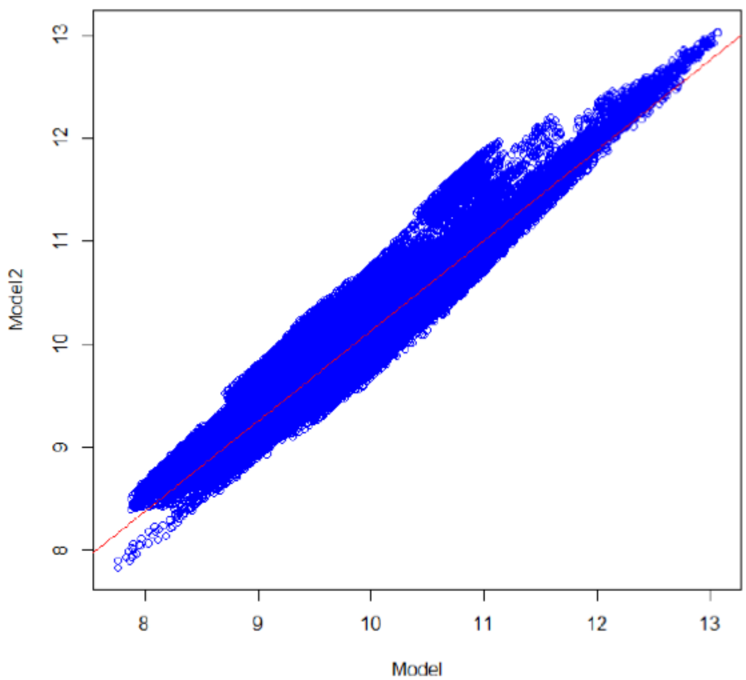


Figure E-25. Simple linear regression between existing (model) and system potential (model2) scenarios.

Commented [NE(49]:
I don't understand what this figure explains

Appendix E References

Adams, T.N., and K. Sullivan. 1989. The physics of forest stream heating: a simple model. Timber, Fish, and Wildlife, Report No. TFW-WQ3-90-007. Washington State Department of Natural Resources, Olympia, WA.

Bothwell, M. L. (1985). Phosphorus limitation of lotic periphyton growth rates: An intersite comparison using continuous-flow troughs (Thompson River system, British Columbia) 1. Limnology and oceanography, 30(3), 527-542.

Boyd, M. S. (1996). Heat source: stream, river and open channel temperature prediction.

Butkus, S., 2011. Memorandum: Dissolved Oxygen Model Development and Evaluation. Laguna de Santa Rosa: TMDL Development and Planning. California Regional Water Quality Control Board North Coast Region. Santa Rosa, CA.

Carroll, J., S. O'Neal, and S. Golding, 2006. Wenatchee River Basin Dissolved Oxygen, pH, and Phosphorus Total Maximum Daily Load Study. Washington State Department of Ecology, Olympia, WA. Publication No. 06-03-018.

Chapra, S.C., 1997. Surface Water-Quality Modeling. McGraw-Hill, New York, N.Y.

Chen, Y. D., Carsel, R. F., McCutcheon, S. C., & Nutter, W. L. (1998a). Stream temperature simulation of forested riparian areas: I. WatersheE-scale model development. Journal of Environmental Engineering, 124(4), 304-315.

Chen, Y. D., McCutcheon, S. C., Norton, D. J., & Nutter, W. L. (1998b). Stream temperature simulation of forested riparian areas: II. Model application. Journal of Environmental Engineering, 124(4), 316-328.

Collins, B.D., Montgomery, D.R. and Sheikh, A.J., 2003. Reconstructing the historical riverine landscape of the Puget Lowland. Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA, pp. 79-128.

Ecology, 2015. TTools for ArcGIS. Washington State Department of Ecology, Olympia, WA. www.ecy.wa.gov/programs/eap/models html

Flynn, K. and M. W. Suplee. 2011. Using a computer water quality model to derive 20 numeric nutrient criteria: Lower Yellowstone River. WQPBDMSTECH-22. Helena, MT: Montana Dept. of 21 Environmental Quality.

Hanus, M.L., D.D. Marshall, and D.W. Hann, 1999. Height-Diameter Equations for Six Species in the Coastal Regions of the Pacific Northwest. Forest Research Laboratory. Oregon State University. Corvallis, OR.

Kennedy, J.T and H. Nicholas, 2013. Memorandum: Shade-QUAL2Kw Configuration for French Creek and Pilchuck River (Revised). Prepared for: United States Environmental

Protection Agency Region 10 and Washington Department of Ecology. Prepared by: Tetra Tech, Inc. Research Triangle Park, NC.

Keyser, Chad E. comp. 2008 (revised August 24, 2015). Southeast Alaska and Coastal British Columbia (AK) Variant Overview – Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 38p.

Mathieu, N. 2014. Addendum to Quality Assurance Project Plan: French Creek and Pilchuck River Temperature, Dissolved Oxygen, and pH Total Maximum Daily Load. Washington State Department of Ecology Water Quality Program, P.O. Box 47600, Olympia, WA, 98504-7600 Publication No. 14-03-112.
https://fortress.wa.gov/ecy/publications/SummaryPages/1403112 html

Mathieu, N. 2016. Addendum 2 to Quality Assurance Project Plan: French Creek and Pilchuck River Temperature, Dissolved Oxygen, and pH Total Maximum Daily Load. Washington State Department of Ecology Water Quality Program, P.O. Box 47600, Olympia, WA, 98504-7600 Publication No. 16-03-115.
https://fortress.wa.gov/ecy/publications/SummaryPages/1603115 html

Mohamedali, T. and S. Lee, 2008 Bear-Evans Watershed Temperature and Dissolved Oxygen Total Maximum Daily Load: Water Quality Improvement Report. Washington State Department of Ecology, Olympia, WA. Publication No. 08-10-058.

Neilson, B.T., A.J. Hobson, N. vonStackelberg, M. Shupryt., and J. Ostermiller, 2014. Chapter 11: Using QUAL2Kw modeling to support nutrient Criteria Development and Wasteload Analysis in Utah. Draft: Technical Basis for Utah's Nutrient Strategy.

Pelletier, G. and S. Chapra, 2008. QUAL2Kw: a modeling framework for simulating river and stream water quality. User's Manual, Theory and documentation.
http://www.ecy.wa.gov/programs/eap/models html

Pelletier, 2013. RMA xls - River metabolism analyzer for continuous monitoring data. Washington State Department of Ecology, Olympia, WA.
www.ecy.wa.gov/programs/eap/models html

Pelletier, 2015. Shade xls: a tool for estimating shade from riparian vegetation. Washington State Department of Ecology, Olympia, WA. www.ecy.wa.gov/programs/eap/models html

Rier, S. T., & Stevenson, R. J. (2006). Response of periphytic algae to gradients in nitrogen and phosphorus in streamside mesocosms. Hydrobiologia, 561(1), 131-147.

Sanderson, T.L. and P.J. Pickett, 2014. A Synopsis of Model Quality from the Department of Ecology's Total Maximum Daily Load Technical Studies. Washington State Department of Ecology, Olympia, WA. Publication No. 14-03-042.

Sargeant, D., B. Carey, M. Roberts, and S. Brock, 2006. Henderson Inlet Watershed Fecal Coliform Bacteria, Dissolved Oxygen, pH, and Temperature Total Maximum Daily Load Study. Washington State Department of Ecology, Olympia, WA. Publication No. 06-03-012.

Snouwaert, E. and T. Stuart, 2015. North Fork Palouse River Dissolved Oxygen and pH Total Maximum Daily Load: Water Quality Improvement Report and Implementation Plan. Washington State Department of Ecology, Spokane, WA. Publication No. 15-10-029.

Swanson, T., A. King, N. Gurdian, and J. Zhen, 2012. French Creek and Pilchuck River Temperature, Dissolved Oxygen, and pH Total Maximum Daily Load Water Quality Study Design (Quality Assurance Project Plan). Washington State Department of Ecology, Olympia, WA. Publication No. 12-03-114.
https://fortress.wa.gov/ecy/publications/SummaryPages/1203114 html

Turner, D., B. Kasper, P. Heberling, B. Lindberg, M. Wiltsey, G. Arnold, and R. Michie, 2006. Appendix 3: Algae/Aquatic Weeds, Dissolved Oxygen and pH TMDL Supplemental Information. CHAPTER 4 of Umpqua Basin Total Maximum Daily Load (TMDL) and Water Quality Management Plan (WQMP). Oregon Department of Environmental Quality. Medford, OR.

Uehlinger, U., Bührer, H. and Reichert, P., 1996. Periphyton dynamics in a floodprone prealpine river: evaluation of significant processes by modelling. Freshwater Biology, 36(2), pp.249-263.